AN ADAPTIVE HYSTERESIS BAND CURRENT CONTROLLED UNIFIED POWER QUALITY CONDITIONER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
In
Power Control and Drives

By

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NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008, INDIA.

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CERTIFICATE

This is to certify that the thesis entitled "**An Adaptive Hysteresis Band Current Controlled Unified Power Quality Conditioner**", submitted by **Mr. Avinash Kumar** in partial fulfillment of the requirements for the award of **Master of Technology in Electrical Engineering** with specialization in "**Power Control and Drives**" at National Institute of Technology, Rourkela. A bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements. The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a master of technology degree in Electrical Engineering.

Place: Rourkela

Date:

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AVINASHKUMAR
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Dedicated to my beloved Parents

CONTENTS

ABSTRACT

Presence of Harmonics is one of the major power quality problems in the present power system. It is demanded that the utility should ideally provide a balanced and pure sinusoidal three-phase voltage of constant amplitude to the loads. But, with the excessive use of non-linear loads power distribution system is getting polluted by harmonics and reactive power disturbances. Harmonics cause a number of undesirable effects like heating, equipment damage and Electromagnetic Interference effects in the nearby communication system. Active power filter (APF) or Active power line conditioner (APLC) is a suitable solution to compensate the adverse effects of harmonics and reactive power simultaneously.

There are various topologies of APFs, one of them is Unified power Quality Conditioner which has two inverters that share same dc link. In this work a three-phase–three wire UPQC, is proposed for harmonic compensation at point of common coupling (PCC) which are present due to the presence of non-linear load. Reference signals were generated using synchronous reference frame theory. While the gating signals were generated using Adaptive Hysteresis Band Current Controller. Conventionally hysteresis band current controller was used for generating the gating signal, for its improved stability, fast transient response, simple implementation & higher accuracy in current tracking. But with the limitation of fixed hysteresis band, made the switching frequency uneven which caused acoustic noise and difficulty in designing input filters. In this work, an Adaptive Hysteresis Band Current Controller (AHCC) has been proposed which maintains the switching frequency nearly constant; by changing the hysteresis bandwidth according to system parameters, such as, modulation frequency, supply voltage, dc capacitor voltage and slope of the reference current signal.

Simulation of the proposed UPQC model was done using MATLAB/SIMULINK and result shows that it achieves superior capability of mitigating the effects of voltage sag/swell and reduces the THD of source current within the IEEE standard of harmonic limit.While AHCC successfully maintains the switching frequency almost constant.

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CHAPTER 1

INTRODUCTION

1. Introduction

Over the last two decades the growth of the digital economy implies a widespread use of electronic equipment not only in the industrial sector, but in the domestic environment too. Studies undertaken in the different countries on the consumption of electricity conclude that office and telecommunication equipment used in nonresidential sector consume about 3 to 4% of the annual consumption of electricity. This will not bring about a greater demand for power, but it would require a higher level of power quality and Reliability (PQR). It has been estimated that more than 30% of the power currently being drawn from the utility companies is heading for sensitive equipment, and this is increasing [2].

The reliability of the power supply delivered by the utilities varies considerably, and depend on a number of factor like lightning, large switching load, nonlinear load stresses or accident can disrupt the electric power grid. Primarily the infrastructure of grid was designed to serve "analog electric device" like lights or motors. These devices are generally tolerant to voltage fluctuations in the power supply system. But the electronic devices demand for higher power quality and reliability stems from the fact that semiconductor components require low-voltage direct current and highly sensitive to short power interruptions, voltage surges and sags, harmonics and other wave form distortions.

On the other hand, with the excessive use of non-linear loads (ASD, Computers, Laser printers, SMPS, Rectifier etc.) power distribution system is getting polluted by harmonics and reactive power disturbances. Harmonics cause a number of undesirable effects like heating, equipment damage, lamp flicker, sensitive-equipment frequent dropout and Electromagnetic interference effects in the power system. The effect of such non-linearity may become sizeable over the next few years. Hence it is very important to overcome these undesirable features.

Passive filter have been conventionally used to eliminate current harmonics and improve the power factor, but not without their disadvantages. The filtering characteristic of the passive filter is strongly affected by the system impedance that may create series or parallel resonance causing amplification of harmonic voltage or current at a specific frequency. They have the limitations of fixed compensation and large size. The increased severity of harmonics pollution in power system has attracted the attention of power systand power electronics engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipment are generally known as active power filters [7], [11].

Active filters can be classified based on converter type, topology, and the number of phases. The converter type can be either CSI or VSI bridge structure. The topology can be shunt, series, or a combination of both. The third classification is based on the number of phases, such as two-wire (single phase) and three- or four-wire three-phase systems.

Voltage-source converter based active filters (AF's) are increasingly being used in power applications to mitigate these PQ problems in power distribution systems [2], [8]. A shunt converter (also known as the shunt active power filter) can compensate all kinds of current related problem such as current harmonics compensation, reactive power compensation, power factor improvement and load unbalance compensation [11]. A series converter (series active power filter) can compensate for voltage sag/swell and distortion at PCC so that the voltage across a sensitive/critical load terminal is perfectly regulated. One modern and very promising solution for the power quality problem is the unified power-quality conditioner. UPQC is a custom power device that consists of shunt and series converters connected back to back on the dc side and deals with load current and supply-voltage imperfections [8].

In this work SRF based controller for the UPQC ,which mainly compensate the reactive power along with voltage and current harmonics of a nonlinear load is implemented. Conventional methods require the measurement of load current, source current, DC link voltage and filter current for shunt APF and source and injection transformer voltage for the series APF. The proposed control strategy based on sensing source current, source voltage, DC link voltage and voltage across PCC, so that the numbers of current measurements are reduced and the system performance is improved. For fixed hysteresis band current controller, the switching frequency varies over a wide range. But for practical application, it is necessary to keep switching frequency within certain limit, with the help of adaptive hysteresis band current control method the switching frequency is kept nearly constant. A design criterion is described for the selection of power circuit component. In MATLAB/SIMULINK different Simulink model with different load condition and different parameters have been developed to validate the performance of controller.

1.1 Background

1.1.1 Power Quality

Power quality, like quality in other goods and services, is difficult to quantify. There is no single accepted definition of quality power. There are standards for voltage and other criteria that may be measured, but the ultimate measure of power quality is determined by the performance and productivity of end-user equipment. If the electric power is inadequate for those needs, then the "quality" is lacking.

The European Council directive on product Liability (85/374/EEC) explicitly qualifies electricity as a product and, like any other product, should satisfy the proper quality requirement. However, electric energy is a very specific product. The possibility of storing electrical energy to any significant quantity is very limited, so it consumed at the instant it is generated. Measurement and evaluation of the quality of the supplied power has to be made at the instant of its consumption [2].

There are many approximations to the term power "quality". A well-known definition based on the principle of EMC, is as follows [2]. The term "Power quality" refers to a wide variety of electromagnetic phenomena that characterize voltage and current at a given time and at a given location on the power system. It is possible to link it with power reliability, service quality and supply quality. Usually it has been sufficient to distinguish between: "voltage quality" and "continuity of supply" [2].

Voltage quality (internationally used term: "Power quality") can be interpreted as the quality of the product delivered by the utility to the customers. The power supply system can only control the quality of the voltage, it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits. Any significant deviation in the waveform magnitude, frequency or purity is a potential power quality problem. Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage. Power quality is often considered as a combination of voltage and current quality. In most of the cases, it is considered that the network operator is responsible for voltage quality at the point of Common coupling (PCC) while the customer's load often influences the current quality at the point of common coupling.

- The current resulting from a short circuit cause the voltage to sag or disappear completely as the case may be.
- Current from lightning strokes passing through the power system cause high impulse voltage.
- Distorted currents from harmonics-producing loads also distort the voltage across PCC as they pass through the system impedance, thus a distorted voltage is presented to other end users.

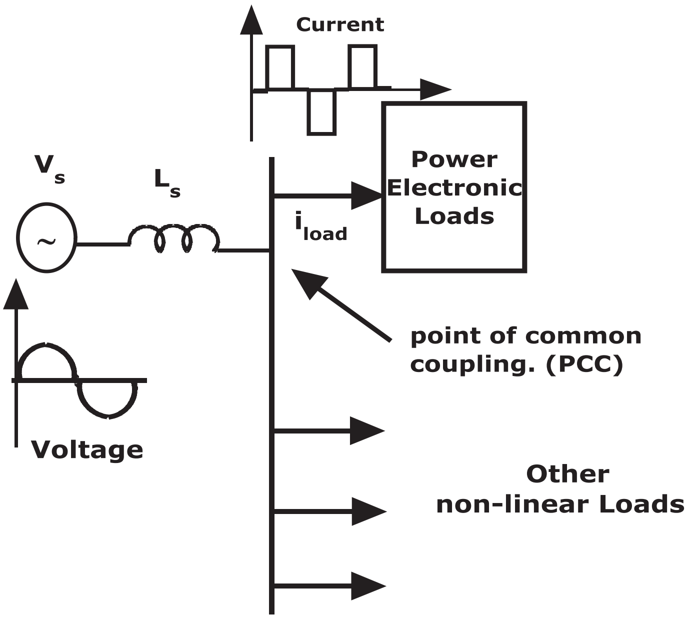


Fig. 1.1 systematic diagram of a power system with nonlinear load.

Figure 1.1 shows a systematic diagram of power system in which generating unit v_s is connected with the load through a transmission line whose impedance is L_s. Where, other kinds of loads (linear and nonlinear loads) are connected across PCC with a power electronics load. Presence of nonlinear loads distort the load current as well as line current, which will also distort the voltage across PCC as they pass through the system impedance. Thus a distorted voltage is present to other end users. Therefore while it is the voltage with which we are ultimately concerned, we must also address phenomena in the current to understand the basic of many power quality problem.

Voltage Sag (dip)

A decrease to between 0.1 and 0.9 pu in rms voltage at the power frequency for duration of 0.5 cycle to 1 min. When the decrease is to essentially zero volts (less than 0.1 pu) it is considered as a short interruption [2]. Voltage sags are generally related with system faults but can also be caused by energization of heavy loads or starting of large motors and overloaded wiring. The term sag describes a short-duration voltage decrease. Although the term has not been formally defined, it has been increasingly accepted and used by utilities, manufacturers and end users. IEC definition for this phenomenon is “dip”. The two terms are considered interchangeable, with sag being the preferred synonym in the U.S. power quality community. Terminology used to describe the magnitude of a voltage sag is often confusing. A “15 percent sag” can refer to a sag which results in a voltage of 0.85 or 0.15pu. The preferred terminology would be one that leaves no doubt as to the resulting voltage level: “a sag to 0.85 pu” or “a sag whose magnitude was 15 percent”. When not specified otherwise, a 15 percent sag will be considered an event during which the rms voltage decreased by 15 percent to 0.85pu. The nominal or base, voltage level should also be specified . Voltage sag problems in industrial equipment include relays opening due to the dip affecting the relay’s coil voltage, under voltage sensors on the AC mains operating unnecessarily, incorrect reports from sensors, such as air flow sensors or water pressure sensors, circuit breakers or fuses operating, either due to the increase in current on non-dipped phases or (more often) due to a large increase in current immediately after the dip or a small section of highly-sensitive electronics that responds incorrectly to the sag.

Voltage Swell

An increase in rms voltage or current at the power frequency for duration from 0.5 cycles to 1 min. The voltage swells are usually associated with system fault conditions, but they are not as common as voltage sags. One way that a swell can occur is from the temporary voltage rise on the un faulted phases during a single line to ground fault. Swells can also be caused by switching off a large load or energizing a large capacitor bank, insulation breakdown, sudden load reduction and open neutral connection. Voltage swells can negatively affect the performance of sensitive electronic equipment, cause data errors, produce equipment shutdowns, may cause equipment damage and reduce equipment life. It causes nuisance tripping and degradation of electrical contacts

1.1.3 Current harmonics

The harmonic voltage and current distortion are strongly linked with each other because harmonic voltage distortion is mainly due to non-sinusoidal load currents. Current harmonic distortion requires over-rating of series components like transformers and cables.

As the series resistance increases with frequency, a distorted current will cause more losses than a sinusoidal current of the same rms value. Types of equipment that generate current harmonics are single-phase loads, switched mode power supplies, electronic fluorescent lighting ballasts, small Uninterruptible Power Supply (UPS) units and variable speed drives. The problems caused by current harmonics are overloading of neutrals, overheating of transformers, nuisance tripping of circuit breakers, over-stressing of power factor correction capacitors and skin effect.

1.1.4 Solution to power quality problems

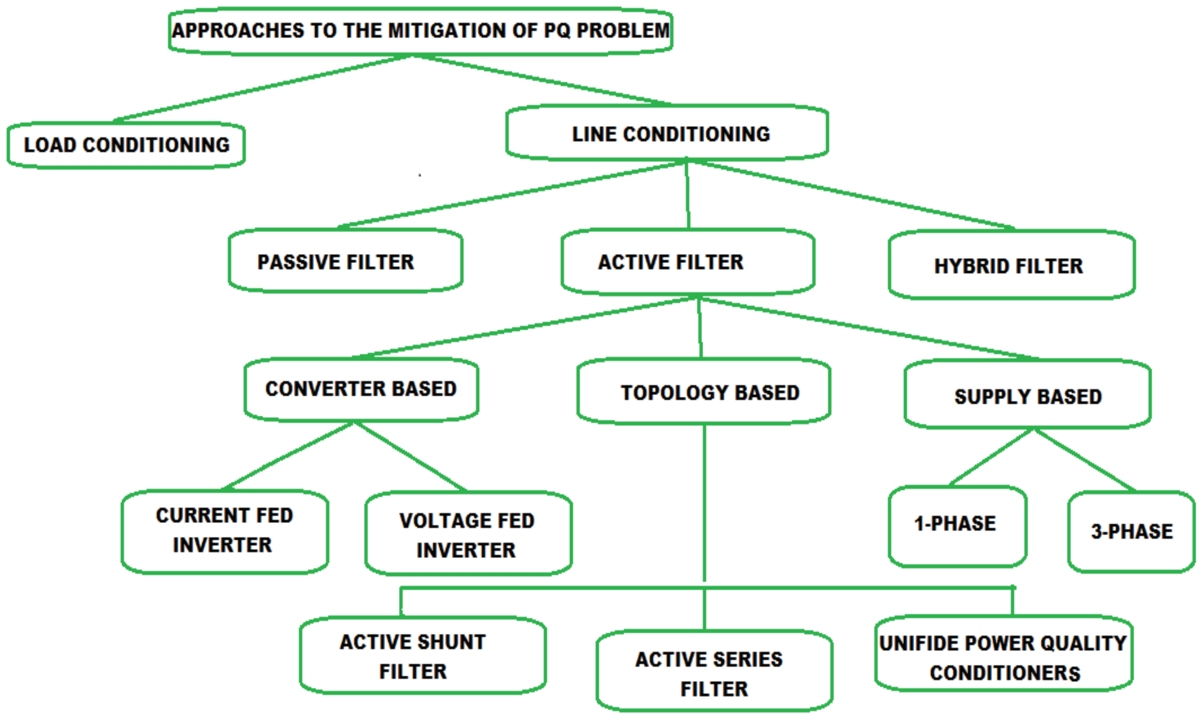


Fig: 1.4 Approaches to mitigation of PQ problem

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is made less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line-conditioning systems that suppress or counteract the power system disturbances. Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. They are usually custom designed for the application. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system. Among the different new technical options available to improve power quality, active power filters have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution systems. The idea of active filters is relatively old, but their practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active power filters are becoming a viable alternative to passive filters and are gaining market share speedily as their cost becomes competitive with the passive variety. Through power electronics, the active filter introduces current or voltage components, which cancel the harmonic components of the nonlinear loads or supply lines, respectively.

1.2 Methodology of Research

In this thesis a three-phase bridge rectifier with R-L load is considered as a non-linear load. To study the transient response of the active power filter an R-L load is connected across the existing load at time t = 0.1 sec. and it is removed at t = 0.2 sec. A unified power quality conditioner is used which mainly compensate the reactive power along with voltage and current harmonics of this locally connected non-linear load. The control scheme is indirect current control scheme which is based on sensing of source current, source voltage, DC link voltage and voltage across PCC, so that the numbers of current measurements are reduced and the system performance is improved. For that different control algorithms, Simulink model were developed and their performances were analysed by the time domain simulation using MATLAB/Simulink simulation package.

First of all, to generate the switching frequency fixed hysteresis band current controller was used. The reference signals were generated by synchronous reference frame method. The generated reference signal, reference current or reference voltage was compared with the line current or voltage across PCC respectively in the fixed band hysteresis current controller to produce switching signals. The total harmonic distortion (THD) in the source current and voltage across PCC was calculated and the DC link capacitor voltage response both at the time of load perturbation was recorded and taken as reference for future.

For fixed hysteresis band current controller, it was observed that the switching frequency varies over a wide range. But for practical application, it is necessary to keep switching frequency within certain limit.

Finally an adaptive hysteresis band current control strategy was implemented to overcome the demerits of fixed band hysteresis current control technique i.e. uncontrolled switching frequency resulting in increased switching losses and excessive ripples in the source current. The proposed scheme was verified from simulation results.

1.3 Objective:

The objectives of the research are:

(1) Design of Unified power quality conditioner based on synchronous reference frame method for compensation of reactive power along with voltage and current harmonics.

(2) Generation of switching frequency based on fixed hysteresis band current controller.

(3) Generation of switching frequency based on adaptive hysteresis band current controller.

To achieve the first and second objective, fixed hysteresis band current controller was used. The reference signals were generated by synchronous reference frame method. The generated reference signal, reference current or reference voltage was compared with the line current or voltage across PCC respectively in the fixed band hysteresis current controller to produce switching signals. For fixed hysteresis band current controller, it was observed that the switching frequency varies over a wide range. But for practical application, it is necessary to keep switching frequency within certain limit. That's why we designed the adaptive hysteresis band current controller.

An adaptive hysteresis band current control strategy was implemented to overcome the demerits of fixed band hysteresis current control technique i.e. uncontrolled switching frequency resulting in increased switching losses and excessive ripples in the source current. The proposed scheme was validated from the simulation results

1.3 Thesis outline

The thesis structure is organised as follows:

Chapter 1 briefly cover introduction to power quality, power quality problems and different approaches to mitigate the power quality problems. Apart from it voltage sag, voltage swell, and methodology of research is also describes in this chapter.

Chapter 2 Starting from linear and non-linear load, this chapter covers basic definitions of harmonics along with analytical expressions for electrical parameters under non-sinusoidal conditions. Harmonic indices, problem caused by harmonics are also discussed briefly in this chapter.

Chapter 3 briefly cover classification of active power filter based on type of converters, topologies and type of loads. On the basis of type of converter it is classified into two types that are voltage source inverter and current source inverter. Whereas on the basis of connection of active power filter that is, on the basis of topologies of active power filter it is classified in three categories that are shunt active power filter, series active power filter and unified power quality conditioner. To meet the requirement of different kind of non-linear loads on supply system active power filters are basically classified into three categories Two wire (1-$\boldsymbol{\Phi}$) , Three wire (3-$\boldsymbol{\Phi}$) and four wire (3-$\boldsymbol{\Phi}$). Apart from it, the advantage and disadvantage of different active power filters are also discussed in this chapter.

Chapter 4 describes the design and control algorithm of unified power quality conditioner. In design part the selection of active power filter component like solid state device, inductor to filter out the switching ripple current, dc link capacitor and reference voltage are briefly explained. Apart from it the basics of control algorithm like signal conditioning, derivation of compensating signal and generation of gating signals for active power filter are disused in details.

Chapter 5 provide the simulation results and discussion. For simulation study an ideal three phase voltage source of constant amplitude is taken while the non-linear load consist of uncontrolled rectifier with a series RL load in DC side. To observe the transient response a parallel resistor is connected in the DC side of the rectifier at t = 0.1 sec, and it is removed at t= 0.2 sec. First of all, to generate the switching frequency fixed hysteresis band current controller was used. The reference signals were generated by synchronous reference frame method. The generated reference signal, reference current or reference voltage was compared with the line current or voltage across PCC respectively in the fixed band hysteresis current controller to produce switching signals. The total harmonic distortion (THD) in the source current and voltage across PCC was calculated and the DC link capacitor voltage response both at the time of load perturbation was recorded. For fixed hysteresis band current controller, it was observed that the switching frequency varies over a wide range. But for practical application, it is necessary to keep switching frequency within certain limit. So, an adaptive hysteresis band current control strategy was implemented to overcome the demerits of fixed band hysteresis current control technique i.e. The proposed scheme was verified from simulation results.

Chapter 6 presents conclusion and scope for future work followed by references and appendices.

CHAPTER 2

HARMONICS

2.1 Introduction

Power systems are designed to operate at frequencies of 50 or 60Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are a form of electrical pollution known as power system harmonics.

Unlike transient events such as lightning that last for a few microseconds, or voltage sags that last from a few milliseconds to several cycles, harmonics are steady-state periodic phenomena that produce continuous distortion of voltage and current waveforms. These periodic non sinusoidal waveforms are described in terms of their harmonics, whose magnitudes and phase angles are computed using Fourier analysis. Jean Bapiste Fourier, a French mathematician developed a mathematical way to investigate a complex wave and express it in a form that is simple and useful. He formulated that a periodic non-sinusoidal function of a fundamental frequency f may be expressed as the sum of sinusoidal functions of frequencies which are multiples of fundamental frequency. Ideally, an electricity supply should invariably show a perfectly sinusoidal voltage signal at every customer location. But because of various reasons utilities often find it hard to preserve such desirable conditions. The deviation of voltage and/or current waveforms from sinusoidal is described in terms of waveform distortion, often expressed as harmonic distortion.

Primarily the infrastructure of grid was designed to serve "analog electric device" like lights or motors. These devices are generally tolerant to voltage fluctuations in the power supply system. At that time harmonic distortion was mainly caused by saturation of transformers, industrial arc furnaces and other arc devices like large electric welders. Still the problem was under control due to conservative design of power equipment and the common use of delta-grounded wye connections in distribution transformers. But the electronic devices demand for higher power quality and reliability stems from the fact that semiconductor components require low-voltage direct current and highly sensitive to short power interruptions, voltage surges and sags, harmonics and other wave form distortions.
A situation that has raised waveform distortion level in distribution networks even further is the application of capacitor banks used in industrial plants for power factor correction and by power utilities for increasing voltage profile along distribution lines. The resulting

reactive impedance forms a tank circuit with the system inductive reactance at a certain frequency likely to coincide with one of the characteristic harmonics of the load. This condition will trigger large oscillatory currents and voltages that may stress the insulation. This situation imposes a serious challenge to industry and utility engineers to pin-point and to correct excessive harmonic distortion levels on the waveforms because its steady increase happens to take place right at the time when the use of sensitive electronic equipment is on the rise [2].

2.2 Linear and Non-linear Loads

2.2.1 Linear Load

A linear load does not change the shape of the waveform of the current, but may change the relative timing (phase) between voltage and current. In other words the current waveform resembles the applied voltage waveform. For example current through a purely resistive element, according to Ohm's law is given by

$$i(t) = \frac{v(t)}{R} \tag{1}$$

If the voltage waveform is purely sinusoidal then the current will also be purely sinusoidal without any distortions at constant temperature.

Voltage and current waveform in a circuit involving inductor make voltage lead current. On the other hand for a circuit involving capacitor, current leads voltage. Hence the two waveforms will be out of phase from one another on both the cases. However, there will be no waveform distortion. In case of linear load power factor is defined as the ratio of real power to apparent power i.e.

$$\text{Power factor} = \frac{\text{Real power}}{\text{Appearent power}} = \cos\Phi \tag{2}$$

Table 2.1 *Examples of Linear loads*

Resistive elements	Inductive elements	Capacitive elements
• Incandescent lighting	• Induction motors	• Insulated cables
• Electric heaters	• current limiting reactors	• Under grounded cables
	• Damping reactors used to attenuate harmonics	• Power factor correction capacitor banks
	• Tuning reactors in harmonic filters	• Capacitors used in harmonic filters
	• Induction generators (wind mills)	

The table 2.1 shows a list of linear loads keeping in mind that instruments are not supplied from any power conversion devices and are free from magnetic core losses and magnetic saturation [2].

2.2.2 Non-linear Loads

Non-linear loads change the shape of the current waveform from a sine wave to some other form. Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current. Example of non-linear load is a power electronic devices. As we know the current-voltage relationship of a diode or BJT, we can say that current can be described as $I = F(V)$ or $i(t) = f(t)$. However when these solid state devices are used to form complex systems like converter, inverter or switch-mode power supplies (SMPS), the current-voltage relationship becomes complex and difficult to express analytically. Few non-linear loads are listed in table 2.2

Table 2.2 *Examples of Non-linear loads*

Power electronics	ARC devices
• Power converters	• Fluorescent lighting
• Variable frequency drives	• ARC furnaces
• DC motor controllers	• Welding machines
• Computer	
• Refrigerator	
• Cranes	
• Elevators	
• Steel mills	
• Power supplies	
• UPS	
• Battery charger	
• Inverters	
• Laser Printer	
• Electronic ballast	

In linear circuits having only sinusoidal currents and voltages of one frequency, the power factor arises only from the difference in phase between the current and voltage. This is "displacement power factor". The concept can be generalized to a total, distortion, or true power factor where the apparent power includes all harmonic components. This is of importance in practical power systems that contain non-linear loads such as rectifiers, some forms of electric lighting, electric arc furnaces, welding equipment, switched-mode power supplies and other devices.

Distortion power factor

The distortion power factor describes how the harmonic distortion of a load current decreases the average power transferred to the load.

$$\text{Distortion power factor} = \frac{1}{\sqrt{1+THD_i^2}} = \frac{I_{1,rms}}{I_{rms}} \tag{3}$$

THD_i is the total harmonic distortion of the load current. This definition assumes that the voltage stays undistorted (sinusoidal, without harmonics). $I_{1,rms}$ is root mean square value of the fundamental component of the current and I_{rms} is the root mean square value of the total current. The result when multiplied with the displacement power factor (DPF) is the overall, true power factor or just power factor (PF):

$$\text{PF} = \text{DPF x Distortion Power factor} = \text{DPF}\,\frac{I_{1,rms}}{I_{rms}} \tag{4}$$

2.3 Analysis of non-sinusoidal periodic function

According to Jean Bapiste Fourier any periodic non-sinusoidal function of a fundamental frequency f may be expressed as the sum of sinusoidal functions of frequencies which are multiples of fundamental frequency.

When a function *f(t)* satisfies the following conditions (known as Dirichlet conditions):

1. *f(t)* is periodic function having a period of *T*
2. *f(t)* is single-valued everywhere
3. In case it is discontinuous, *f(t)* has finite number of discontinuities in any one period.
4. *f(t)* has finite number of maxima and minima in any one period.

Then according to Fourier theorem *f(t)* may be represented in the trigonometric form by the infinite series

$$f(t) = a_0 + a_1 \cos(\omega_0 t) + a_2 \cos(2\omega_0 t) + a_3 \cos(3\omega_0\, t) \ldots\ldots\ldots\ldots a_n \cos(n\omega_0 t)$$
$$+ b_1 \sin(\omega_0\, t) + b_2 \sin(2\omega_0\, t) + b_3 \sin(3\omega_0 t) \ldots\ldots\ldots\ldots.. b_n \sin(n\omega_0 t)$$
$$= a_0 + \sum_{n=1}^{\infty} \{a_n \cos(n\omega_0\, t) + b_n \sin(n\omega_0 t)\} \qquad (5)$$

We can further simplify equation 2.1 which yields

$$f(t) = C_0 + \sum_{n=1}^{\infty} C_n \sin(n\omega_0 t + \Phi_n) \qquad (6)$$

Where $C_0 = a_0, C_n = \sqrt{{a_n}^2 + {b_n}^2}$ and $\Phi_n = \tan^{-1}(\frac{a_n}{b_n})$

Equation 2.2 represent a periodic function *f(t)* made up of the combination of sinusoidal functions of different frequencies

In equation 2.2

$C_n \sin(n\omega_0 t + \Phi_n)$	n^{th} harmonic of periodic function
C_0	Magnitude of DC component
C_n	Magnitude and phase angle of n^{th} harmonic component
Φ_n	Phase angle of n^{th} harmonic component

The component for n =1 is called fundamental component. Magnitude and phase angle of each harmonic determine the resultant waveform *f(t).*

The value of a_0, a_n and b_n can be evaluated using basic integral calculus theorems. The values are given as below

$$a_0 = \frac{1}{T}\int_0^T f(t)dt \qquad (7)$$

$$a_n = \frac{2}{T}\int_0^T f(t) \cos\frac{2\pi n}{T} t\, dt \qquad (8)$$

$$b_n = \frac{2}{T}\int_0^T f(t) \sin\frac{2\pi n}{T} t\, dt \qquad (9)$$

2.4 Power definitions under non-sinusoidal waveform

Under non-sinusoidal conditions different power system quantities such as apparent, active and reactive power, power factor etc. are quite different from those under ideal sinusoidal conditions. The set of power definitions established by C. I. Budeanu is popularly used under steady-state analysis. That is given below:

1. **Apparent power (*S*):** Apparent power is a product of rms voltage and rms current in a circuit. It is defined as

$$S = V_{rms} \times I_{rms}$$

Where $V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2\,(t)dt} = \sqrt{\sum_{n=1}^{\infty} V_n{}^2}$

And $I_{rms} = \frac{1}{T}\int_0^T i^2\,(t)dt = \sum_{n=1}^{\infty} I_n{}^2$

Here V_n and I_n corresponds to the rms value of the nth order harmonic components of the Fourier series and T is the period of fundamental component.

2. **Active power (P):** Active power is the power delivered as an output in the form of electric power, mechanical power, thermal power etc. It is defined as

$$P = \sum_{n=1}^{\infty} P_n = \sum_{n=1}^{\infty} V_n\, I_n \cos \Phi_n$$

Where Φ_n is the displacement angle of each pair of nth order harmonic voltage and current components.

3. **Reactive power (Q):** Reactive power is an amplitude of power oscillation with no net transfer of energy and is caused by energy storage components such as capacitor and inductor. It is defined as

$$Q = \sum_{n=1}^{\infty} Q_n = \sum_{n=1}^{\infty} V_n\, I_n \sin \Phi_n$$

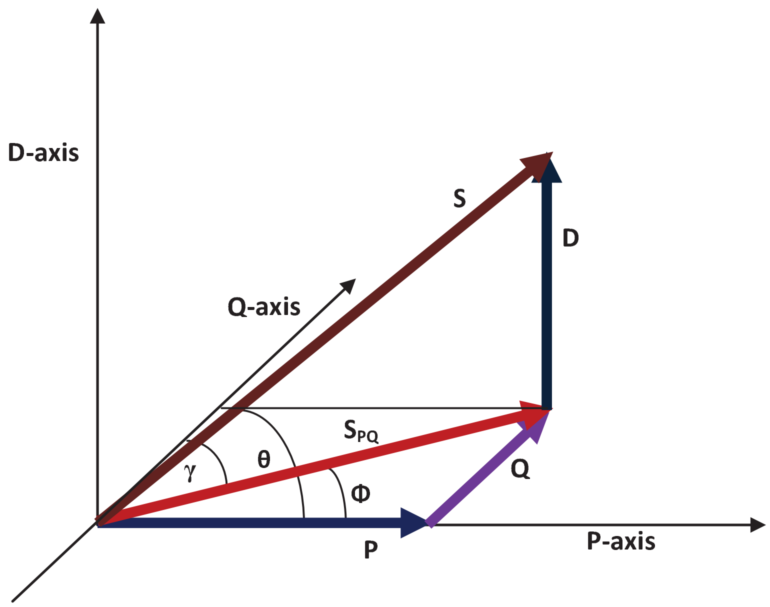


Fig. 2.1 The power tetrahedron

4. **Complex power (SPQ):** complex power is given by

$$S_{PQ} = P + jQ = \sum_{n=1}^{\infty} V_n \, I_n \cos \Phi_n + \sum_{n=1}^{\infty} V_n \, I_n \sin \Phi_n$$

5. **Distortion power (D):** Distortion power is given as

$$D = \sqrt{S^2 - |S_{PQ}|^2} = \sqrt{S^2 - P^2 - Q^2}$$

6. **Power factor (λ):** $\lambda = \cos\theta = \frac{P}{S}$

7. **Displacement factor (cos Φ):** $\cos\Phi = \frac{P}{|S_{PQ}|}$

8. **Distortion factor (cos γ) :** $\cos\gamma = \frac{|S_{PQ}|}{S}$

2.5 Harmonic indices

Harmonic indices are important parameters to assess the operation of a power system. There are numerous of them defined in the literature. These harmonic indices not only influence the development of measuring instruments but also affect the mitigation strategies [20]. Among various indices, two most commonly used indices for measuring the harmonic content of a waveform are given below

2.5.1 Total Harmonic Distortion (THD):

The total harmonic distortion or THD is a measure of effective value of the harmonic components in a distorted waveform. It can be defined as potential heating value of the harmonics relative to the fundamental. In [21] it is defined as

$$THD = \sqrt{\frac{Sum\ of\ all\ squares\ of\ amplitude\ of\ all\ harmonic\ voltages}{square\ of\ the\ amplitude\ of\ the\ fundamental\ voltage}} \times 100$$

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} {M_h}^2}}{M_1}$$

Where M_h is the rms value of harmonic component h of the quantity M. The THD is a very useful quantity for many applications. It is the most commonly used harmonic index. However, it has the limitation that it is not a good indicator of voltage stress within a capacitor because that is related to the peak value of voltage waveform.

2.5.2 Total Demand Distortion (TDD):

Current distortion level expressed by THD can be sometimes misleading because a small current may have a high THD but not a significant threat to the system. Many adjustable-speed drives exhibit high THD but because of small magnitude of current they are harmless. Therefore IEEE has recommended use of another harmonic measurement by referring THD to fundamental of peak demand load current. It is called total demand distortion and given by

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} {I_h}^2}}{I_L}$$

Where I_L is the peak or maximum demand load current at the fundamental frequency component measured at the point of common coupling (PCC). It is calculated as the average of the maximum demand current for the preceding 12 months.

2.6 Problems caused by harmonics

Harmonic currents cause problems both on the supply system and within the installation. Some of the major adverse impacts of power system harmonics are discussed below.

2.6.1 Harmonic problems within the installation

Problems caused by harmonic currents:

◆ **Overloading of neutrals:** In a three-phase system the voltage waveform from each phase to the neutral star point is displaced by 120° so that, when each phase is equally loaded, the combined current in the neutral is zero. When the loads are not balanced only the net out of balance current flows in the neutral. However, although the fundamental currents cancel out, the harmonic currents do not in fact those that are an odd multiple of three times the fundamental, the 'triple-N' harmonics, add in the neutral

◆ **Overheating of transformers:** There are two major effects of harmonic current on transformer as given below and all of them result in increased transformer heating.

(i) Harmonic current results in increased transformer rms current higher than its capacity resulting in more conductor losses.
(ii) As eddy current loss increases with square of frequency, harmonic current increases this loss.

◆ **Nuisance tripping of circuit breakers:** Residual current circuit breakers (RCCB) operate by summing the current in the phase and neutral conductors and, if the result is not within the rated limit, disconnecting the power from the load. Nuisance tripping can occur in the presence of harmonics. The RCCB, being an electromechanical device, may not sum the higher frequency components correctly and therefore trips erroneously. Nuisance tripping of miniature circuit breakers (MCB) is usually caused because the current flowing in the circuit is higher than that expected from calculation or simple measurement due to the presence of harmonic currents.

◆**Over-stressing of power factor correction capacitors:** Power factor correction capacitors are provided in order to draw a current with a leading phase angle to offset lagging current drawn by an inductive load such as induction motors. Figure 14 shows the effective equivalent circuit for a PFC capacitor with a non-linear load. The impedance of the PFC capacitor reduces as frequency rises, while the source impedance is generally inductive and increases with frequency. The capacitor is therefore likely to carry quite high harmonic currents and, unless it has been specifically designed to handle them, damage can result.

◆ **Skin effect:** Alternating current tends to flow on the outer surface of a conductor. This is known as skin effect and is more pronounced at high frequencies. Skin effect is normally ignored because it has very little effect at power supply frequencies but above about 350 Hz, i.e. the seventh harmonic and above, skin effect will become significant, causing additional loss and heating.

Problems caused by harmonic voltages:

◆ **Voltage distortion:** The distorted load current drawn by the non-linear load causes a distorted voltage drop across the transmission line due to the impedance of the transmission line. The resultant distorted voltage waveform is applied to all other loads connected to the same point of common coupling.

◆ **Induction motors:** Harmonic voltage distortion causes increased eddy current losses in motors in the same way as in transformers. However, additional losses arise due to the generation of harmonic fields in the stator, each of which is trying to rotate the motor at a different speed either forwards or backwards. High frequency currents induced in the rotor further increase losses.

◆ **Zero-crossing noise:** Many electronic controllers detect the point at which the supply voltage crosses zero volts to determine when loads should be turned on. This is done because switching reactive loads at zero voltage does not generate transients, so reducing electromagnetic interference (EMI) and stress on the semiconductor switching devices. When harmonics or transients are present on the supply the rate of change of voltage at the crossing becomes faster and more difficult to identify, leading to erratic operation. There may in fact be several zero-crossings per half cycle.

2.6.2 Problems caused when harmonic currents reach the supply

When a harmonic current is drawn from the supply it gives rise to a harmonic voltage drop proportional to the source impedance at the point of common coupling (PCC) and the current. Since the supply network is generally inductive, the source impedance is higher at higher frequencies. Of course, the voltage at the PCC is already distorted by the harmonic currents drawn by other consumers and by the distortion inherent in transformers, and each consumer makes an additional contribution.

2.7 Summary

Power electronics devices offer valuable industrial and domestic equipment applications but at the same time it increases the non-linear characteristics of the system, which cause a number of undesirable effects like harmonic distortion, low system efficiency, poor power factor and interference in nearby communication system. The term "harmonics" is becoming very common for both for the electric utilities and end users of electric power. This chapter covers basic definitions of harmonics along with analytical expressions for electrical parameters under non-sinusoidal conditions. Harmonic currents are the result of wide use of non-linear loads. As long as we choose to employ these loads, we have to deal with the reality of existence of harmonics. A brief discussion about various sources of harmonics that have become concern for electric industry along with most relevant adverse effects of harmonics in different situations is presented in this chapter.

CHAPTER 3

LINE CONDITIONING

3.1 Introduction

There are basically two approaches to mitigate the power quality problem. First approach is known as load conditioning, which ensures that the equipment is made less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other approach is to install line-conditioning systems that suppress or counteract the power system disturbances. Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. They are usually custom designed for the application. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system.

Among the different new technical options available to improve power quality, active power filters have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution systems. The idea of active filters is relatively old, but their practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active power filters are becoming a viable alternative to passive filters and are gaining market share speedily as their cost becomes competitive with the passive variety. Through power electronics, the active filter introduces current or voltage components, which cancel the harmonic components of the nonlinear loads or supply lines, respectively.

3.2 Active Power Filter

The simplest method of harmonic filtering is with passive filters. They use reactive storage components, namely capacitors and inductors. Among the more commonly used passive filters are the shunt-tuned LC filters and the shunt low-pass LC filters. They have some advantages such as simplicity, reliability, efficiency, and cost. Among the main, disadvantages are the resonances introduced into the ac supply; the filter effectiveness, which is a function of the overall system configuration; and the tuning and possible detuning issues. These drawbacks are overcome with the use of active power filters. Most of the active power filter topologies use voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device. The voltage source inverters are more dominant over current source inverter because it is lighter, Cheaper and expandable to multilevel and multistep version. Figure 3.1 shows the classification of active power filter on the basis of Converter type, topology and types of load [1].

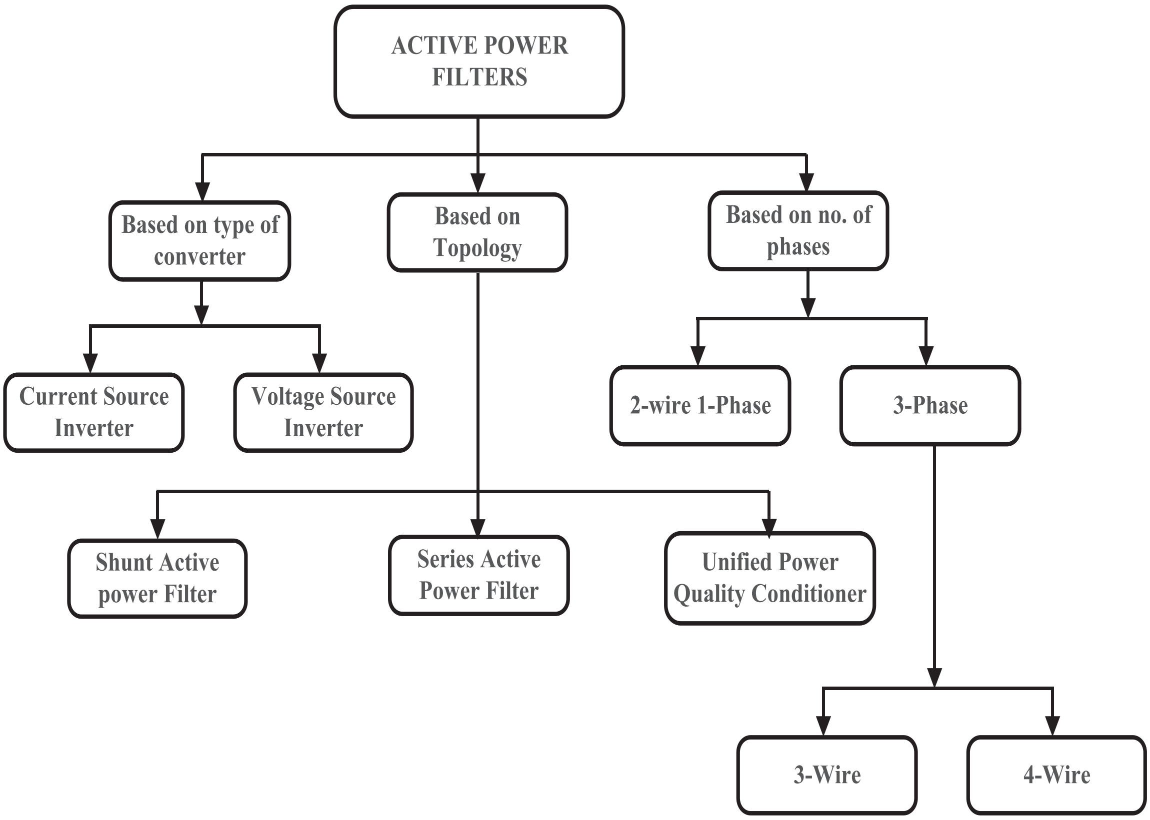


Fig. 3.1 classification of active power filter.

Depending on the particular application or electrical problem to be solved, active power filters can be implemented as shunt type, series type, or a combination of shunt and series active filters (Unified Power Quality Conditioner).

To meet the requirement of the three types of non-linear loads on supply system active power filters are basically classified into ,

- **Two wire (1-Φ) :** To meet the requirement of 1- Φ load Domestic light, ovens,TV's, computers, AC, Xerox machine, Laser Printers etc.

- **Three wire (3-Φ):** Major amount of ac power are consumed by three phase loads such as ASD (AC Adjustable speed drives)
- **Four wire (3-Φ):**To meet the requirement of 1-Φ and 3-Φ load at a time.

3.2.1 Shunt Active Power Filter

The voltage waveform at a power system bus is affected by the current injected at that bus. A 'stiff' system is one for which the voltage is rather insensitive to current, while the voltage at a "weak" system bus is quite sensitive to current. There fore providing that a system is not too stiff, a non sinusoidal voltage waveform at a bus can be corrected to sinusoidal by injecting the proper current magnitude and waveform. This is the basic principle of an active power line conditioner.

Shunt active power filter usually connected across the loads to compensate all current related problem like current harmonics, power factor improvement, reactive power compensation, Load unbalance compensation and dc link voltage regulation. it act as a current source and inject compensating current at PCC to make the source current sinusoidal and in phase with the source voltage [1].

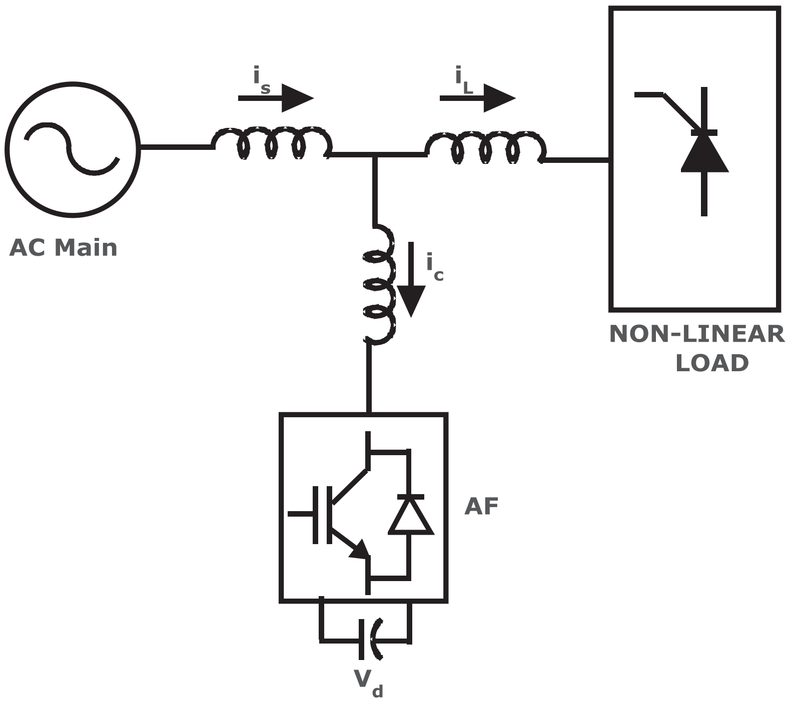


Fig. 3.2 Shunt active power filter.

Figure 3.2 shows the shunt active power filter in which i_s represent source current or line currnet , i_L is load current and i_c is the comensating current injected by the shunt active power filter.

Role of DC side capacitor

The Dc side side capacitor serves two main purpose [7], [3].

1. It maintains a Dc voltage with small ripple in steady state. The level of voltage ripple is very important for two reasons. The peak capacitor voltage is the maximum voltage to be supported by the switches, while the lower capacitor voltage will determine the active power filter capability to force its current to follow the intended refernce wave form.If the capacitor voltage falls below the peak of PCC voltage, active power filter will not be able to shape its current as intended, and hence maloperation may occur.
2. It serves as a energy storage element to supply real power difference between load and source during transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter.

So DC capacitor voltage should be maintained at a reference value. However when load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is compensated by the DC capacitor, which changes the DC capacitor voltage away from the reference voltage.

3.2.2 Series Active Power Filter

Series active power filters were introduced at the end of 1980. It is usually connected in series with a line through a series transformer. It acts as a controlled voltage source and can compensate all voltage related problem like voltage harmonics, voltage sag, voltage swell, etc. Figure 3.4 shows the voltage source converter based series active power filter. In Fig. 3.3 i_s , i_L and V_{AF} represent source current, source voltage and injected voltage by the series transformer respectively. Series connected active power filter protect the voltage sensitive devices like super conductive magnetic-energy storage device, semic-onductor devices and power system devices from an inadequate supply voltage quality.

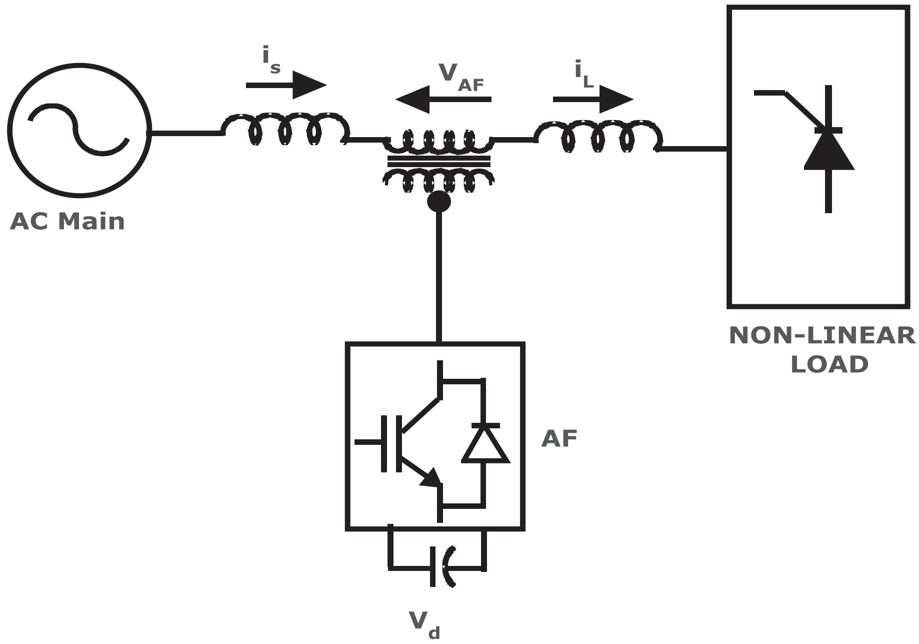


Fig. 3.3 Series active power filter.

In many cases series active power filters are used with passive LC filter. If series active power filter is used with a passive LC filter , the series active power filter work as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than power distribution system. Advantage of this connection is that the rated power of the series active filter is a small fraction of the load KVA rating. However in case of the voltage compensation the apparent power rating of the series active power filter may increase [7].

3.2.3 Unified Power Quality Conditioner

Figure 3.4 shows the system configuration of a unified power quality conditioner (UPQC). It consist of two converters (6-semi-conductor device per converter) connected back to back with same DC-link capacitor. One inverter connected across the load and acts as shunt APF. This converter is controlled as a variable control source such that the load current related power quality problems do not appear across the source terminals. Furthermore, the shunt inverter plays an important role in maintaining a constant and self-supporting DC-bus voltage across two inverters. Second converter is connected in series with the line through a series transformer and functions as a series APF. This converter is controlled as a variable

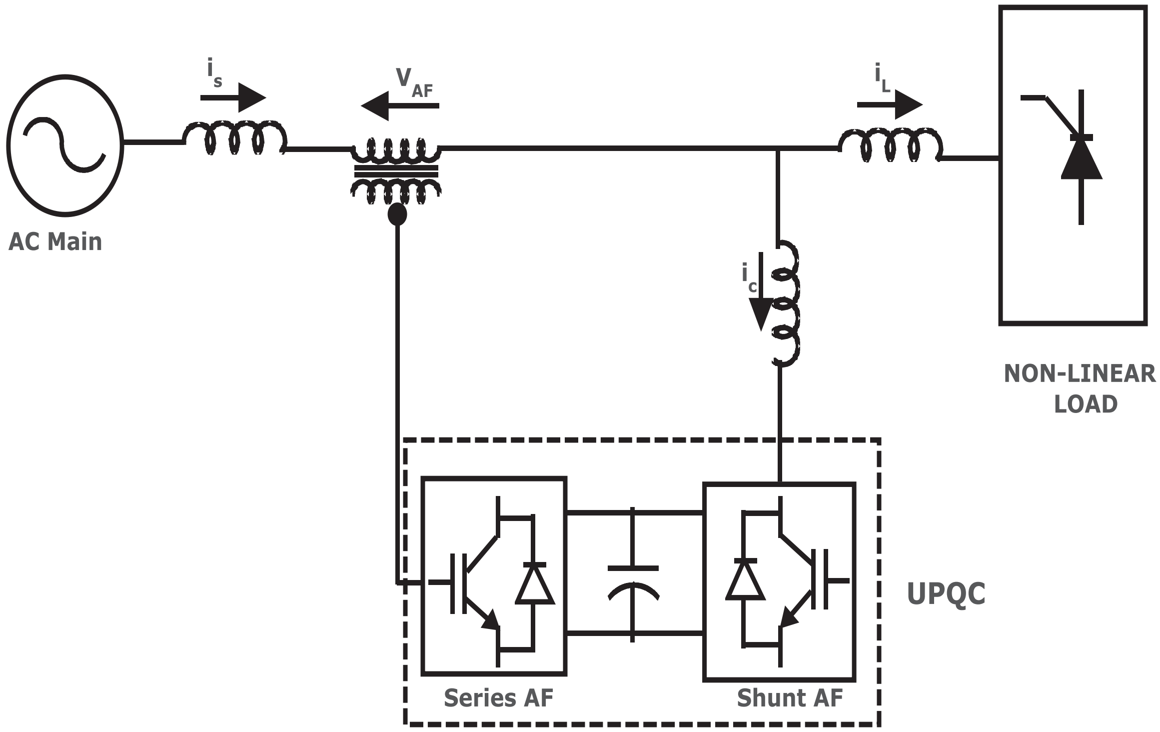


Fig. 3.4 Unified power quality conditioner

Voltage source and it isolates the load bus voltage from disturbances in the voltage at the point of common coupling (PCC). In 3-phase system, the adequate control of shunt and series inverters can support the load reactive power demand and compensate the load current harmonics ,voltage harmonics, voltage sag/swell and voltage flicker [6], [7]. The main drawback of UPQC are its large size and control complexity because of the large number of semiconductor devices involved [1].

3.3 Hybrid Power filter

According to filtering performance active power filters are better than passive filter. But economically active power filters are costly and require comparatively high rating converter. That is why, a combination of active and passive filters, known as hybrid filters are used for economical and improved performance. Out of various topologies of hybrid active filters the most commonly used configuration is shown in fig 3.5.

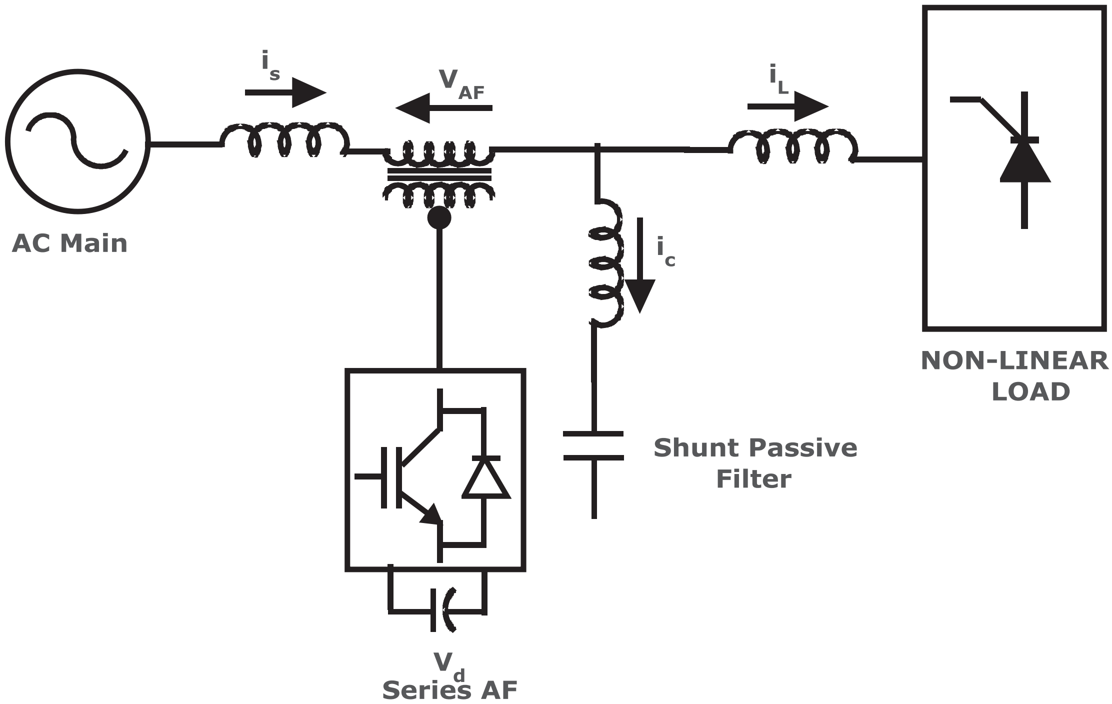


Fig. 3.5 Hybrid Power Filter.

The hybrid filter shown in fig 3.5 consists of a series APF and a shunt passive filter. It is suitable for large rectifier type load, it cannot provide simultaneous control over the output voltage and input current waveform and amplitude, resulting in some distortion of the output voltage [3].

3.4 Summary

This chapter briefly cover classification of active power filter based on type of converters, topologies and type of loads. On the basis of type of converter it is classified into two types that are voltage source inverter and current source inverter. Whereas on the basis of connection of active power filter that is, on the basis of topologies of active power filter it is classified in three categories that are shunt active power filter, series active power filter and unified power quality conditioner. To meet the requirement of different kind of non-linear loads on supply system active power filters are basically classified into three categories Two wire (1-$\boldsymbol{\Phi}$) , Three wire (3-$\boldsymbol{\Phi}$) and four wire (3-$\boldsymbol{\Phi}$). Apart from it, the advantage and disadvantage of different active power filters are also discussed in this chapter. On the basis of performance and cost we can conclude that the hybrid active power filter is better than the shunt and series active power filter. But ultimately it depends on type of load and type of disturbance. For example if we are looking for compensation of current harmonics, the best alternative is hybrid active power filter, whereas for reactive power compensation shunt active power filter is the best one. Likewise for voltage harmonic, voltage regulation and voltage balancing the suitable active power filter is series active power filter, whereas for current harmonic, reactive power, voltage harmonic and voltage regulation Unified active power filter is used.

CHAPTER 4

DESIGN AND CONTROL STRATEGIES

4.1 Selection of component of active power filter

An active power filters are comprises of three basic components that are solid stat device, an inductor to filter switching ripple and dc link capacitor. To achieve good performance of active power filter these three basic components should be select properly.

4.1.1 Solid state device

Solid state device like BJT, MOSFET, IGBT etc. are used for switching purpose in active power filter. Primarily BJT's and MOSFET were used for small rating. Nowadays IGBT is used up to normal rating and GTO's are used for higher rating. Apart from solid state device rating their switching frequency is also an important phenomena for selection of solid state device [1].

4.1.2 Selection of inductor L_c

An inductor is used between voltage source inverter and the supply terminal voltage to filter out the switching harmonic. The selection of inductor value is very crucial. If inductor value is small, large switching ripple are injected into the current. Whereas a large value of inductor $\boldsymbol{L_c}$ will reduce the current ripple but at the same it will not allow the proper tracking of the compensating current because of their lagging nature. So to obtain satisfactory performance an optimum selection of L_c is essential [1].

4.1.3 Selection of DC bus capacitor C_{DC}

The Dc side capacitor serves two main purpose, it maintains a Dc voltage with small ripple in steady state. The level of voltage ripple is very important for two reasons. The peak capacitor voltage is the maximum voltage to be supported by the switches, while the lower capacitor voltage will determine the active power filter capability to force its current to follow the intended refernce wave form.If the capacitor voltage falls below the peak of PCC voltage, active power filter will not be able to shape its current as intended, and hence mal operation may occur.

It serves as a energy storage element to supply real power difference between load and source during transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. So DC capacitor voltage should be maintained at a reference value. However when load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is compensated by the DC capacitor, which changes the DC capacitor voltage away from the reference voltage.

A small value of dc capacitor may lead to a large ripple in the steady state and wide fluctuation in the dc-bus voltage under transient conditions. Whereas a higher value of capacitor reduces fluctuations and ripple in the dc- bus voltage, but the overall cost and size of the system will increase [1], [3].

4.2 Selection of reference voltage

Selection of reference value of DC side capacitor $V_{DC\,ref.}$ is one of the important parameters. The peak capacitor voltage is the maximum voltage to be supported by the switches, while the lower capacitor voltage will determine the active power filter capability to force its current to follow the intended reference wave form. If the capacitor voltage falls below the peak of PCC voltage, active power filter will not be able to shape its current as intended, and hence mal operation may occur.

4.3 CONTROL STRATEGIES of Active Power Filters

Control strategies of active power filters are broadly divided into three stage that are,

1st Stage : Signal Conditioning.

2nd Stage : Derivation of Compensation signal.

3rd Stage : Generation of Gating signals to the devices of active power filter.

4.3.1 Signal Conditioning :

To develop control algorithm several instantaneous voltage and current signals are required. These signals are used to monitor, measure, and record various performance indexes, such as total harmonic distortion (THD), power factor, active and reactive power, crest factor, etc. The voltage signals to be measured are ac, terminal voltages, dc-bus voltage of the active power filter, and voltages across series elements. These voltage signals are generally measured by potential transformer (PT) or Hall effect. The current signals to be sensed are load currents, supply currents, compensating currents, and dc-link current of the active filter. Current signals are sensed using current transformers and/or Hall-effect current sensors. The voltage and current signals are sometimes filtered to avoid noise problems [1].

4.3.2 Derivation of Compensation signal.

Development of compensating signals either in terms of voltages or currents is the important part of AF control and affects their rating and transient, as well as steady-state performance. Control strategies to generate compensation commands are either based on frequency-domain or time-domain correction techniques [4], [8].

In frequency-domain: Control strategy in the frequency domain is based on the Fourier analysis of the distorted voltage or current signals. Using the Fourier transformation, the compensating components are separated from the distorted signals. and combined to generate compensating commands.

In time-domain: In time domain the control strategy is based on instantaneous derivation of compensating command in terms of either voltage or current signal from distorted and harmonics polluted voltage or current signals. There is a large number of control methods in the time domain, which are

- Instantaneous P-Q theory or Instantaneous active and reactive power method.
- Synchronous d-q reference frame method or SRF method.
- Synchronous detection method.
- Flux based controller.
- Notch filter method.
- Sliding mode controller.
- PI controller.

The instantaneous active and reactive power theory (p-q theory) has been widely used and is based on α-β transformation of voltage and current signals to derive compensating signals. In the synchronous d-q reference frame and flux-based controllers, voltage and current signals are transformed to a synchronously rotating frame, in which fundamental signal become dc quantities along d and q axis, and other than fundamental signal all harmonics signal will appear along d and q axis like oscillating components. Then the fundamental components are extracted from the oscillating and dc quantity with the help of low pass filter (LPF). The dc-bus voltage feedback is generally used to achieve a self-supporting dc bus in voltage sourced converter based active filters. In the notch-filter-based method, the compensating commands are extracted using notch filters on distorted voltage or current signals. In PI and sliding-mode controllers, either dc-bus voltage (in a VSI) or dc-bus current (in a CSI) is maintained to the desired value and reference values for the magnitudes of the supply currents are obtained. Subtracting load currents from reference currents, compensating commands are derived [1].

4.3.3 Generation of Gating signals

The last stage of control strategy of the active filter is to generate gating signals for the solid-state devices of the active filter. Based on the derived compensating commands, in terms of voltages or currents, a variety of approaches are available such as

- Hysteresis band current control
- Adaptive hysteresis band current control
- PWM based current or voltage control
- Dead beat control
- Sliding mode current control
- Fuzzy based current control

4.4 Hysteresis band current control

Conventionally Hysteresis band current control method is used for its improved stability, fast transient response, simple implementation & higher accuracy in current tracking. Hysteresis band current control schemes are based on two level hysteresis comparators Fig.4.1.

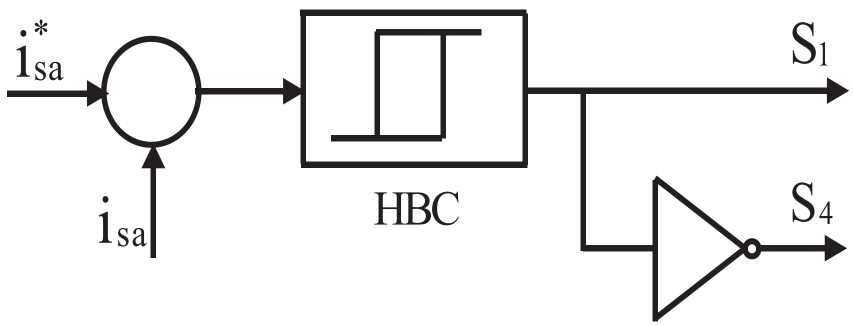


Fig. 4.1 Block diagram of Hysteresis band current controller.

The switching signals are produced directly when the error exceeds an assigned tolerance band Fig. 4.2. If the current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band [4].

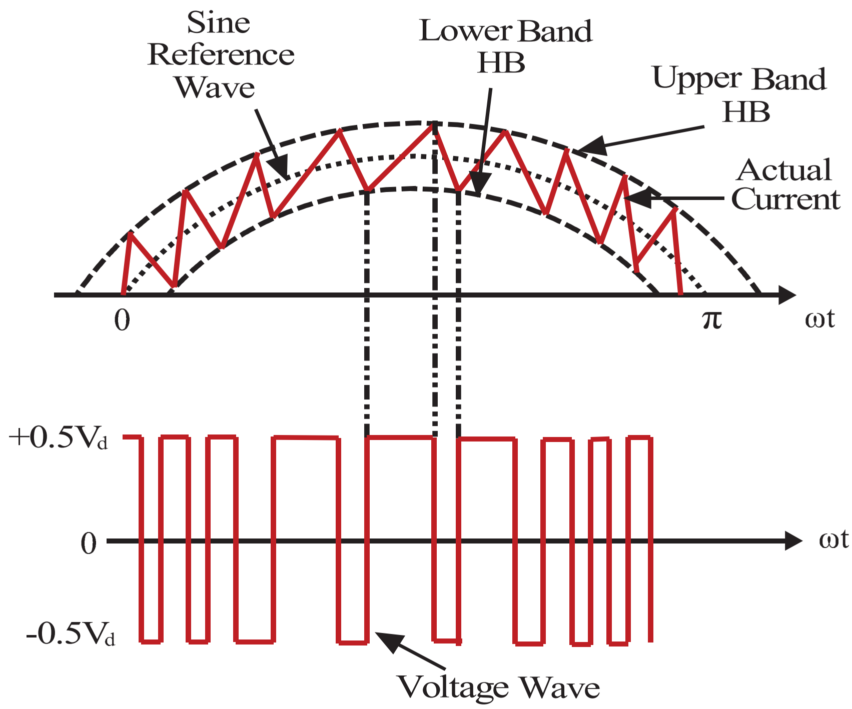


Fig. 4.2 Hysteresis band current control.

Hence, the actual current is forced to track the reference current within the hysteresis band.

4.5 PID Controller

A proportional-integral-derivative controller (PID Controller) is a control loop feedback mechanism basically used in industrial control system. Basically it calculate an error value based on the difference between measured process variable and desired set point, and tries to minimize the error by adjusting the process control input. The PID controller involves three different mode proportional mode, Integral mode and Derivative mode. In 4.1

$$u(t) = Mv(t) = K_p e(t) + k_i \int_0^t e(\mathcal{T})\boldsymbol{d}(\mathcal{T}) + k_d \frac{d}{d(t)} e(t) \qquad (4.1)$$

$Mv(t)$ is the combined effect of PID controller together. $\mathcal{T}$ is an variable of integration , takes an values from time 0 to t. proportional mode determines the reaction to the current error, the integral mode determine the reaction based on recent errors and the derivative mode determines the reaction based on the rate by which the error is changing By adjusting constants in the PID controller algorithm the PID can provide individualized control specific to process requirements including error responsiveness, overshoot of set point and system oscillation as shown in table 4.1.

Table 4.1 Effect of increasing a parameter independently.

Parameter	**Rise time**	**Overshoot**	**Settling time**	**S-S error**	**Stability**
K_P	Decreases	Increases	Small change	Decrease	Degrade
K_i	Decreases	Increases	Increase	Eliminate	Degrade
K_d	Minor Change	Decreases	Decrease	No effect	Improve if K_d is small

Some applications may require only using one or two modes to provide the appropriate system control. A PID controller will be called a PI, PD, P or I controller in the absence of respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise. Proportional mode responds to a change in the process variable proportional to the current measured error value. The proportional response can be adjusted by multiplying the error by a constant K_P, called the proportional gain or proportional sensitivity. With a proportional controller offset (deviation from the set point) is present. Increasing the controller gain will make the system loop go unstable, with proportional controller integral action is included to eliminate the offset. The controller proportional and integral action is known as proportional-integral (PI) controller. With integral controller output is proportional to the amount of time the error is present. Integral action eliminate the offset. While this will force the controller to approach the set point quicker than a proportional controller alone and eliminate steady state error, it also contributes to system instability as the controller will always be responding to past values.

This instability causes the process to overshoot the set point since the integral value will continue to be added to the output value, even after the process variable has reached the desired set point. With derivative action, the controller output is proportional to the rate of change of measurement or error. The controller output is calculated by the rate of change of the measurement with time. Derivative action can stabilize loops since it adds phase lead. If we use derivative action more controller gain and reset can be used.

PI controller are commonly used, since derivative action is sensitive to measurement noise, Whereas the absence of an integral term may prevent the system from reaching the reference value due to control action.

4.6 Summary:

This chapter briefly describes the design and control algorithm of unified power quality conditioner. In design part the selection of active power filter component like solid state device, inductor to filter out the switching ripple current, dc link capacitor and reference voltage are briefly explained. Apart from it the basics of control algorithm like signal conditioning, derivation of compensating signal and generation of gating signals for active power filter are disused in details.

CHAPTER 5

PROPOSED CONTROL STRATEGY AND SIMULATION RESULTS

5.1 System studied

Fig 5.1 shows Unified power quality conditioner. It consists of

1. A three phase voltage source
2. A three-phase bridge diode rectifier with R-L load as non-linear load
3. Two voltage source converters connected back to back with same DC link.
4. A series transformer.
5. Control block.

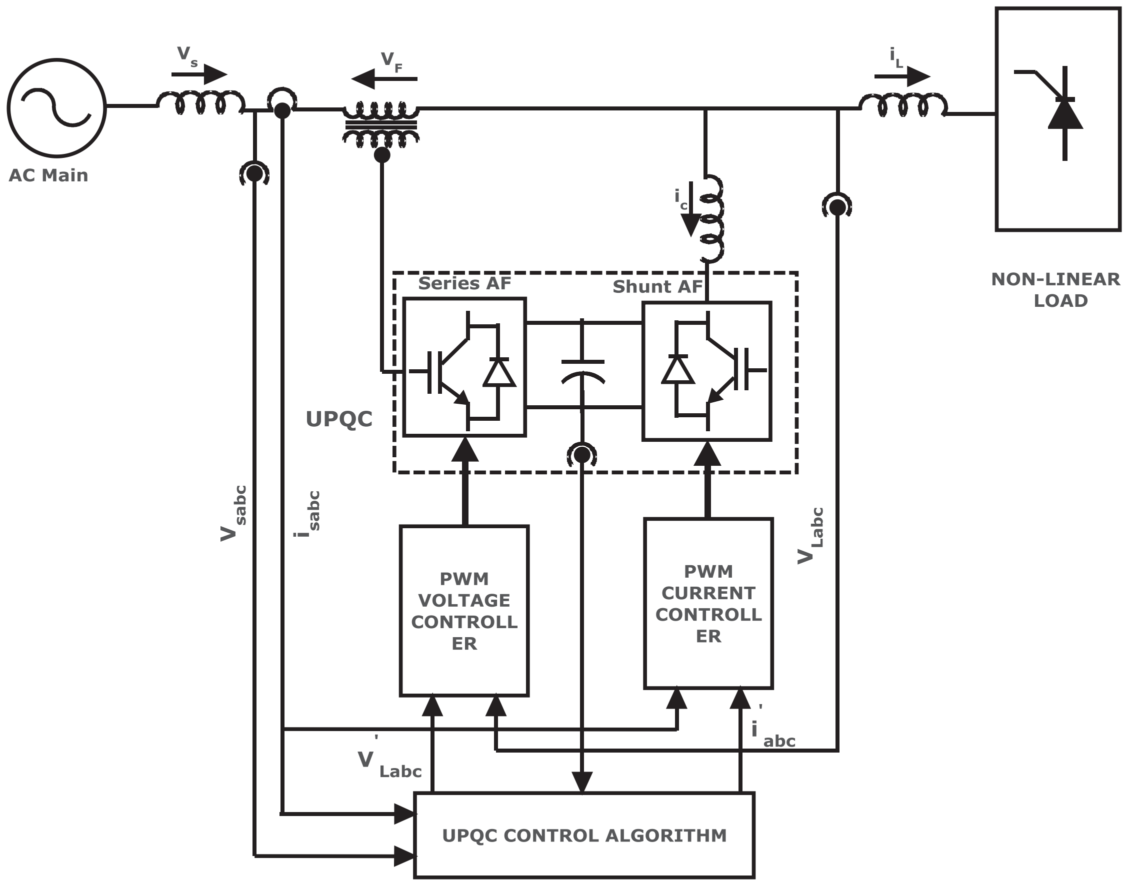


Fig.5.1 Basic compensation scheme of UPQC

The control scheme is based up on indirect current control technique. The inputs to the control block are dc-link capacitor voltage v_{dcref} three phase source currents (i_{sa}, i_{sb} ,i_{sc}) three phase voltages (v_{sa}, v_{sb}, v_{sc}) and voltage across point of common coupling as shown in figure. The outputs of the controller are the gating signals to the devices of PWM converter.

Development of compensating signals either in terms of voltages or currents is the important part of AF control and affects their rating and transient, as well as steady-state performance. Control strategies to generate compensation commands are based on frequency-domain or time-domain correction techniques.

The synchronous reference frame theory or ($d-q$) theory is based on time domain reference signal estimation technique. It performs the operation in steady-state or transient state as well as for generic voltage and current wave form. It allows controlling the APF in real time. Another important characteristic of this theory is the simplicity of calculation, which involves only algebraic calculation. The basic structure of SRF methods consist of direct ($d-q$) and inverse $(d-q)^{-1}$ Park transformation [8]. The reference frame transformation is formulated from a three-phase $a-b-c$ stationary system to the direct axis (d) and quadratic axis (q) rotating system. The instantaneous vectors v_a, i_a are set on the a-axis, v_b, i_b are on the b-axis and v_c , i_c are on the c-axis as shown in Fig. 5.2.

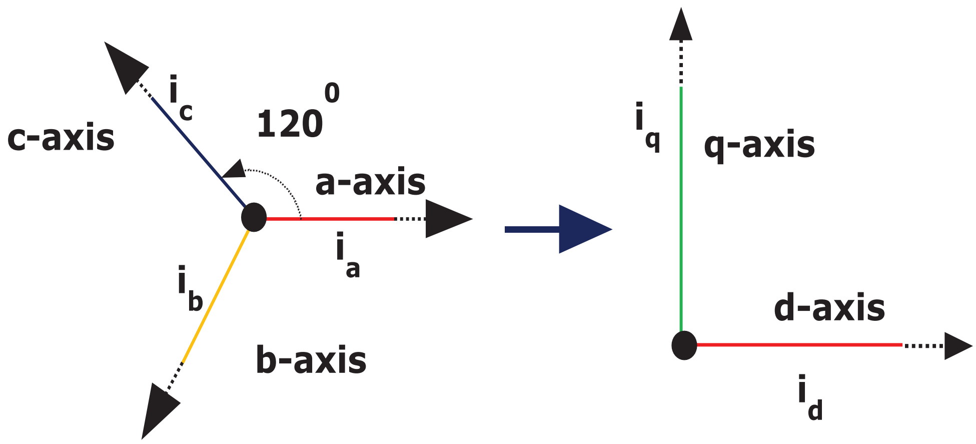


Fig-5.2 a-b-c to d-q-0 transformation

These three phase space vectors stationary coordinates are easily transformed to rotating

$d-q$ frame using Park transformation. For harmonic compensation the distorted currents are first transferred into two-phase stationary coordinates using $\alpha-\beta$ transformation. After that, the stationary frame quantities are transferred into synchronous rotating frame using cosine and sine functions from the phase-locked loop (PLL). The sine and cosine functions help to maintain the synchronization with supply voltage and current. In nonlinear power system the i_d and i_q components of the current include both oscillating components. ($\tilde{\imath}_d$ and $\tilde{\imath}_q$) and average components ($\bar{\imath}_d$ and $\bar{\imath}_q$).

$$i_d = \bar{\imath}_d + \tilde{\imath}_d \qquad \text{and} \qquad i_q = \bar{\imath}_q + \tilde{\imath}_q \tag{1}$$

The oscillating components ($\tilde{\imath}_d$ and $\tilde{\imath}_q$) of the current correspond to harmonic currents, and the average components of the current correspond to the active ($\bar{\imath}_d$) and reactive ($\bar{\imath}_q$) currents [6]. In the balanced and linear three-phase systems, the load voltage and current signals generally consist of fundamental positive-sequence components. However, in unbalanced and nonlinear load conditions, they include fundamental positive-, negative-, and zero-sequence components. In APF applications, the fundamental positive-sequence components of the signals should be separated in order to compensate the harmonics.

5.2 Generation Of Reference Signals

For current and voltage harmonics compensation, the distorted signals are first transferred into two-phase stationary coordinates (using $\alpha-\beta$ transformation). After that, the stationary frame quantities are transferred into synchronous rotating frames using cosine and sine functions from the phase-locked loop (PLL). The sine and cosine functions help to maintain the synchronization with supply voltage. Using low pass filter, the fundamental components are separated easily from distorted signals and transferred back to the $a-b-c$ frame as reference signals for the APF.

Reference-signal Generation for Series APF

SRF-based UPQC control algorithm can solve the PQ problems related with source voltage harmonics, unbalanced voltages, and voltage sag and swell with series APFs. In the proposed method, the series APF controller calculates the reference value to be injected by the series transformers (STs), comparing the positive-sequence component of the source voltages with load-side line voltages. The series APF reference-voltage signal generation algorithm is shown in Fig. 5.3.

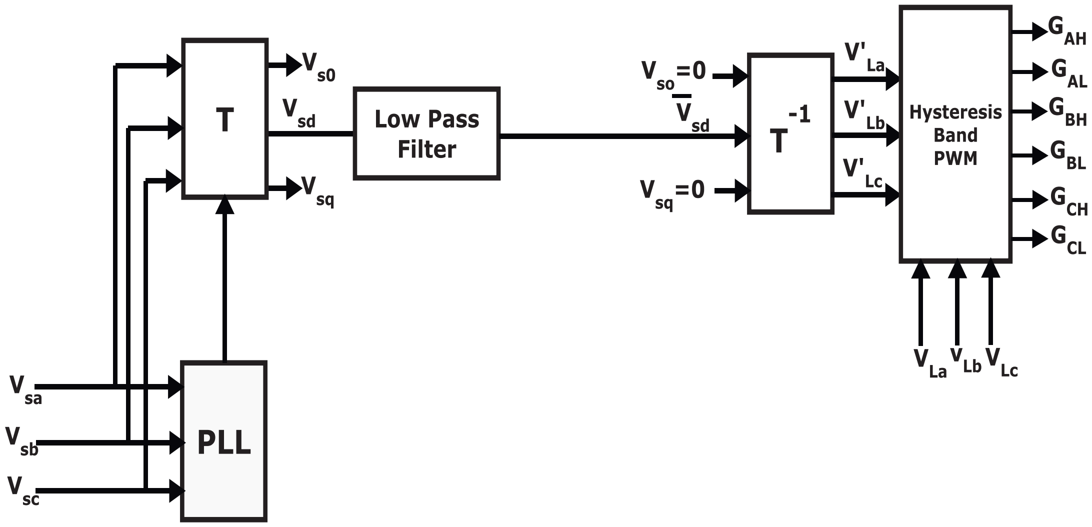


Fig. 5.3 Series APF controller.

In (3), the supply voltages v_{sabc} are transformed to v_{dq0} by using the transformation matrix T given in (2).

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \sin(\omega t) & \sin(\omega t - 2\pi/3) & \sin(\omega t + 2\pi/3) \\ \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} v_{so} \\ v_{sd} \\ v_{sq} \end{bmatrix} = T \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{3}$$

The instantaneous source voltages (v_{sd} and v_{sq}) include both oscillating components ($\tilde{v}_{sd}$ and $\tilde{v}_{sq}$) and average components ($\bar{v}_{sd}$ and $\bar{v}_{sq}$) under unbalanced source voltage with harmonics. The oscillating components $\tilde{v}_{sd}$ and $\tilde{v}_{sq}$ consist of the harmonics and negative-sequence components of the source voltages under distorted load conditions. An average component includes the fundamental components of the source voltages. The zero-sequence part v_{s0} of the source voltage occurs when the source voltage is unbalanced. The source voltage in the d-axis v_{sd} given in (4) consists of the average and oscillating components.

$$v_{sd} = \bar{v}_{sd} + \tilde{v}_{sq} \tag{4}$$

$$\mathrm{T}^{-1} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & \sin(\omega t) & \cos(\omega t) \\ 1/\sqrt{2} & \sin(\omega t - 2\pi/3) & \cos(\omega t - 2\pi/3) \\ 1/\sqrt{2} & \sin(\omega t + 2\pi/3) & \cos(\omega t + 2\pi/3) \end{bmatrix} \tag{5}$$

The load reference voltages v'_{Labc} are calculated as given in (6). The inverse transformation matrix T^{-1} given in (5) is used for producing the reference load voltages by the average component of source voltage and PLL.

$$\begin{bmatrix} v'_{\mathrm{La}} \\ v'_{\mathrm{Lb}} \\ v'_{\mathrm{Lc}} \end{bmatrix} = \mathrm{T}^{-1} \begin{bmatrix} 0 \\ \bar{v}_{\mathrm{sd}} \\ 0 \end{bmatrix} \tag{6}$$

The source-voltage positive-sequence average value ($\bar{v}_{sd}$) in the d-axis is calculated by LPF, as shown in Fig. 3. Zero sequences and q-axis components of source voltage are set to zero in order to compensate load voltage harmonics, unbalance, and distortion. The produced load reference voltages (v'_{La}, v'_{Lb}, v'_{Lc}) and load voltages (v_{La}, v_{Lb}, v_{Lc}) are compared by an adaptive hysteresis band current controller to produce switching signals.

Reference-signal Generation for shunts APF

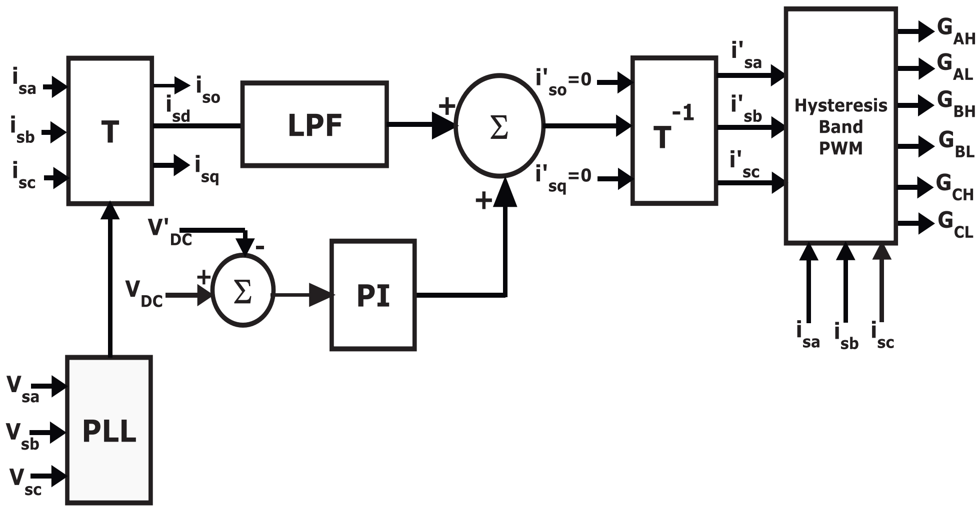


Fig.5.4 Shunt APF Controller

Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180°. The shunt APF reference-voltage signal generation algorithm is shown in Fig. 5.4.

The SRF-based shunt APF reference signal generation algorithm uses only source voltages, source currents, and dc-link voltages. The source current are transformed to $d-q-0$ coordinates, as given in (7).

$$\begin{bmatrix} \mathrm{i}_{s0} \\ \mathrm{i}_{sd} \\ \mathrm{i}_{sq} \end{bmatrix} = \mathrm{T} \begin{bmatrix} \mathrm{i}_{sa} \\ \mathrm{i}_{sb} \\ \mathrm{i}_{sc} \end{bmatrix} \tag{7}$$

In nonlinear load condition, the instantaneous source currents (i_{sd} and i_{sq}) include both oscillating components ($\tilde{\imath}_{sd}$ and $\tilde{\imath}_{sq}$) and average components ($\bar{\imath}_{sd}$ and $\bar{\imath}_{sq}$). The oscillating components consist of the harmonics and negative-sequence components of the source currents. The average components consist of the positive-sequence components of current and correspond to active currents. The zero sequence component of source current (i_{s0}) appears when the load is unbalanced. In order to maintained dc-link voltage at reference value, Some active power should be absorbed from the power system by the shunt APF for regulating dc-link voltage. For this purpose, the dc-link voltage is compared with its reference value (v'_{DC}), and the required active current (i_{dloss}) is obtained by a PI controller. The fundamental reference current is calculated by adding to the required active current and source current average component ($\bar{\imath}_{sd}$), which is obtained by an LPF, as given in (8).

$$i'_{sd} = i_{dloss} + \bar{\imath}_{sd} \tag{8}$$

In this method, the zero- and negative-sequence components of the source current reference (i'_{s0} and i'_{sq}) in the 0- and q-axes are set to zero in order to compensate the harmonics, unbalance, distortion, and reactive power in the source current. The reference source current are calculated as given in (9) to compensate the harmonics, neutral current, unbalance, and reactive power by regulating the dc-link voltage [6].

$$\begin{bmatrix} i'_{sa} \\ i'_{sb} \\ i'_{sc} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ i'_{sd} \\ 0 \end{bmatrix} \tag{9}$$

The produced reference-source currents (i'_{sa}, i'_{sb} and i'_{sc}) and measured source currents (i_{sa}, i_{sb}, i_{sc}) are compared by a hysteresis band current controller to generate switching signals.

5.3 Adaptive hysteresis band current controller

As discussed in chapter 4, conventionally Hysteresis band current control method was used for its improved stability, fast transient response, simple implementation and higher accuracy in current tracking. Apart from it there is some drawback of fixed hysteresis band current controller like uneven switching frequency, as a result acoustic noise is produced and difficulty in designing input filters. But for practical application, it is necessary to keep switching frequency within certain limit.

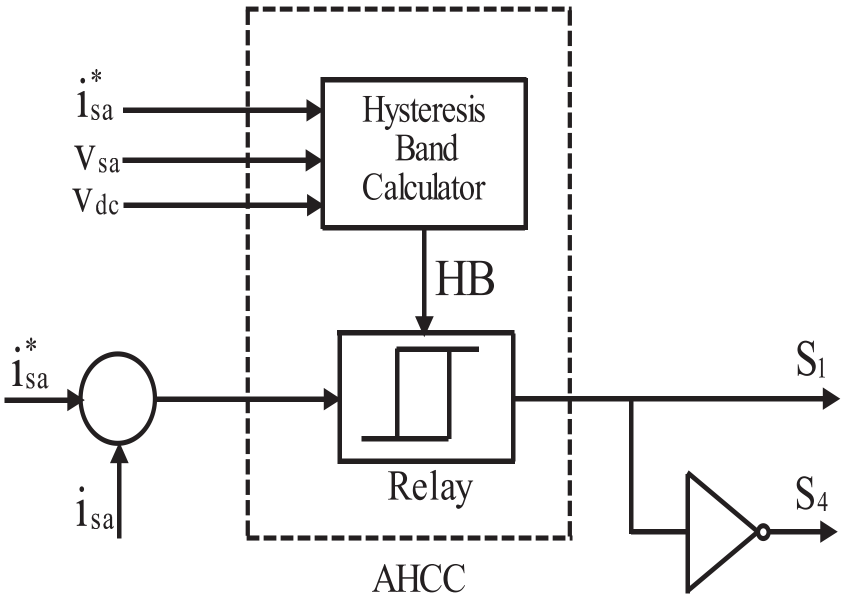


Fig.5.5 Adaptive hysteresis current controller.

To overcome the drawbacks of HBC with fixed hysteresis band an Adaptive Hysteresis Band Current Controller (AHCC) shown in Fig.5.5, proposed by B.K Bose is used, which maintains the switching frequency nearly constant, by changing the hysteresis band according to system parameters (reference current, source Voltage & dc capacitor voltage). Estimation of the hysteresis band for maintaining the switching frequency constant is presented in the next section.

5.4 Estimation of Hysteresis band

The current and voltage waveform for phase ‘a’ is shown in Fig. 5.6 where i_{sa}^{*} is the desired reference source current and i_{sa} is the actual source current. When the source current tries to leave the hysteresis band appropriate switch is turned ON or OFF to force the ramping of the current within the hysteresis band.

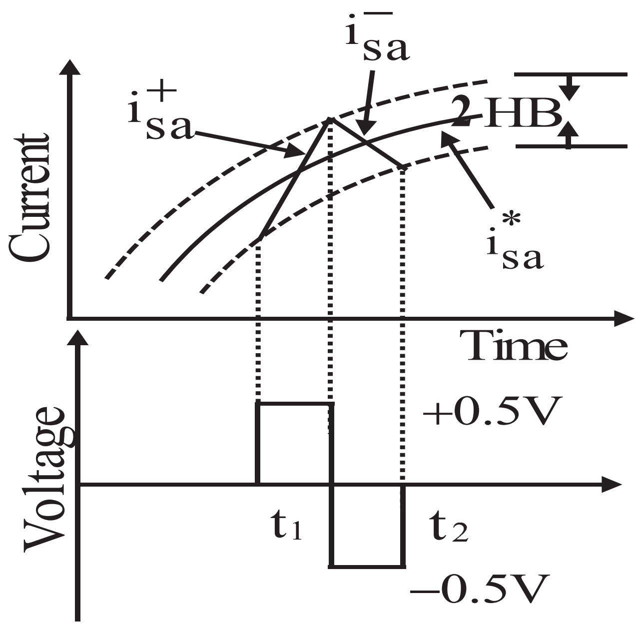


Fig.5.6 Current & Voltage wave form

The following equations can be written in the respective switching intervals $t_1$and $t_2$from Fig.5.6.

$$\frac{di_{sa}^{+}}{dt} = \frac{1}{L}(0.5V_{dc} - V_s) \tag{10}$$

$$\frac{di_{sa}^{-}}{dt} = -\frac{1}{L}(0.5V_{dc} + V_s) \tag{11}$$

Where, L is the filter inductor, $i_{sa}^{+}$and i_{sa}^{-} are the respective rising and falling current segments. From the geometry of Fig 5.6 we can write

$$\frac{di_{sa}^{+}}{dt}t_1 - \frac{di_{sa}^{*}}{dt}t_1 = 2HB \tag{12}$$

$$\frac{di_{sa}^{-}}{dt}t_2 - \frac{di_{sa}^{*}}{dt}t_2 = -2HB \tag{13}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{14}$$

Where, f_c is the switching frequency and i_{sa}^{*} is the desired reference source current. Adding (12) & (13) and substituting in (14), we will get

$$t_1\frac{di_a^{+}}{dt} - t_2\frac{di_a^{-}}{dt} - \frac{1}{f_c}\frac{di_{sa}^{*}}{dt} = 0 \tag{15}$$

Subtracting (12) from (13), we get

$$4HB = t_1\frac{di_a^{+}}{dt} - t_2\frac{di_a^{-}}{dt} - (t_1 - t_2)\frac{di_{sa}^{*}}{dt} \tag{16}$$

Substituting (10) & (11) in (15), we get

$$(t_2 - t_1) = -\frac{2L}{v_{dc}f_{sv}}\left(\frac{v_s}{L} + \frac{di_a^{+}}{dt}\right) \tag{17}$$

Substituting (10) & (11) in (16), we get

$$4HB = \frac{0.5\,v_{DC}}{f_cL} - (t_1 - t_2)\left(\frac{v_s}{L} + \frac{di_{sa}^{*}}{dt}\right) \tag{18}$$

Substituting (17) in (18) and simplifying, we get

$$HB = \frac{0.125v_{dc}}{f_cL}\left[1 - \frac{4L^2}{v_{dc}^2}\left(\frac{v_s}{L} + m^2\right)^2\right] \tag{19}$$

Where,$m = di_a^{*}/dt$ is the slope of desired reference source current waveform. Hysteresis band (HB) calculated in (19) is modulated at different points of fundamental frequency cycle to maintain the switching frequency of the inverter constant [12], [4]. The required gating signal for APF is produced by AHCC, which follow the following switching law to generate the suitable compensating current to be injected at PCC:

- If $i_s < (i_s^{*} - HB)$ The Upper switch of the i^{th}leg is ON and lower switch is OFF,
- If $i_s > (i_s^{*} + HB)$ The Upper switch of the i^{th}leg is OFF and the lower switch is ON,

Here ‘HB’ is the calculated hysteresis band around the reference current.

5.5 Simulation Results

The Matlab/Simulink simulation tool was used to develop a model that allowed the simulation and testing of the SRF method for UPQC, which were implemented in the controller of the unified power quality conditioner for three-phase , three wire system. The UPQC system parameters used in this study are given in table 5.1.

Table 5.1 System Parameters

System Parameters	Values
Source voltage (v_s)	230 V
System frequency (f)	50Hz
Shunt filter impedance (R_{sh}, L_{sh})	4Ω, 3.5mH
Series filter impedance (R_{se}, L_{se})	3Ω, 3mH
Load impedance (R_L, L_L)	6.7Ω, 20mH
DC link capacitance (C_{DC})	2200μF
Reference DC link voltage (V_{DC}^*)	400 V
Switching Frequency	10 KHz

For simulation study an ideal three phase voltage source of constant amplitude Fig. 5.7 is taken, while the non-linear load consist of uncontrolled rectifier with a series RL load in DC side.

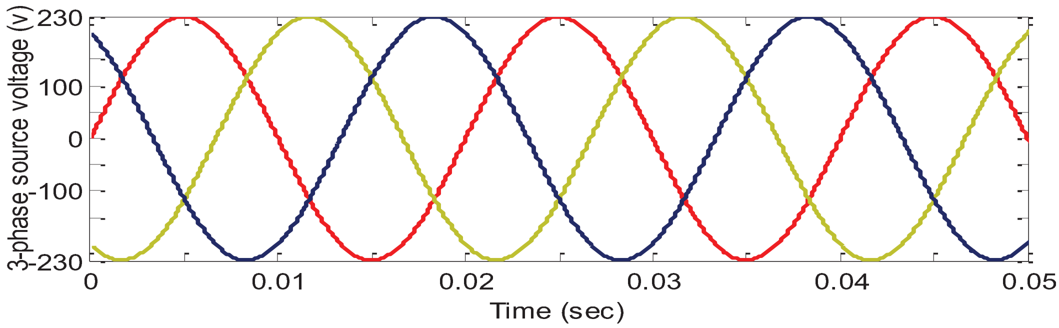


Fig. 5.7 Three phase source voltage of constant amplitude

To observe the transient response a parallel resistor is connected in the DC side of the rectifier at t = 0.1 sec, and it is removed at t= 0.2 sec. Because in a symmetrical three-phase system, the current of each phase is symmetrical, the phase A is selected for the observation and recorded. At first R-L load is connected across a 3-phase uncontrolled rectifier. Since the source voltage is pure sinusoidal as shown in fig. 5.7, load current should be also sinusoidal, but due to presence of the R-L load with rectifier, the load acts as a non-linear load and current through the load becomes non-sinusoidal as shown in Fig. 5.8.

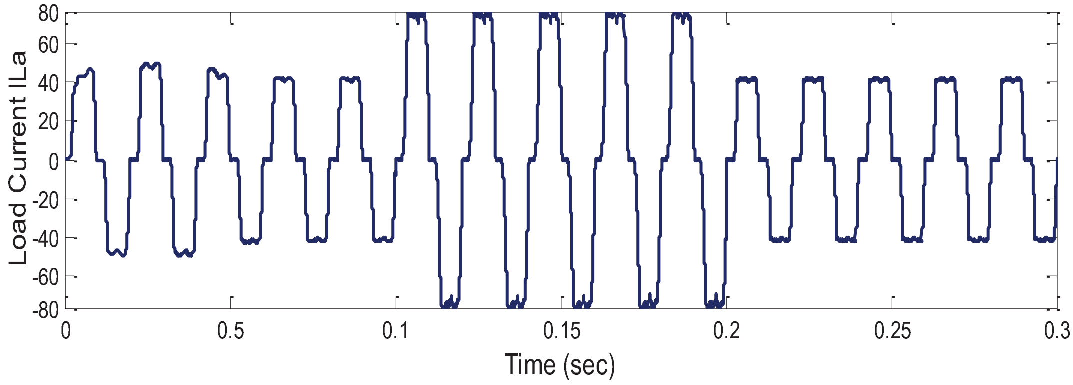


Fig. 5.8 Load current i_{La}

Figure 5.9 shows the FFT analysis of load current which shows that total harmonic distortion in load current is 23.74%.

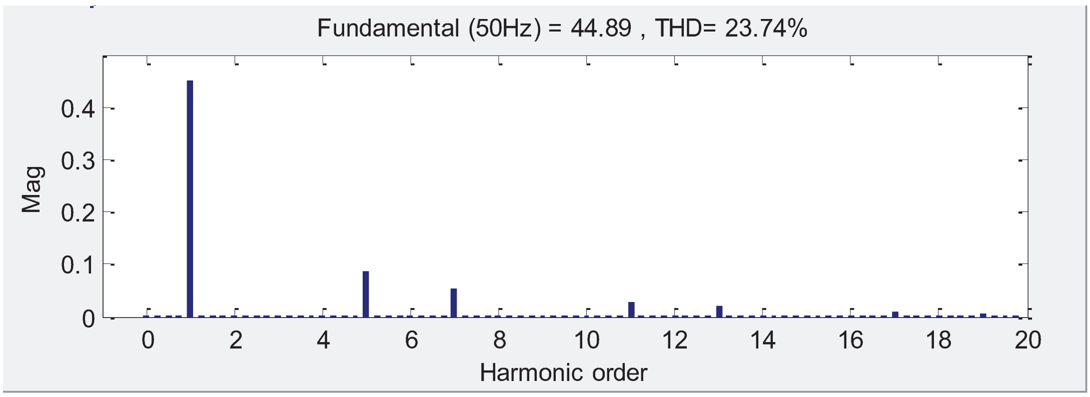


Fig. 5.9 Harmonic spectrum of the non-linear load

In most of the cases, it is considered that, the network operator is responsible for voltage quality at the point of Common coupling (PCC) while the customer's load often influences the current quality at the point of common coupling. Presence of nonlinear loads distort the load current as well as line current, which will also distort the voltage across PCC as they pass through the system impedance. To overcome problems occurring in power system due to presence of non-linear load, active power filter is used. Figure 5.10 shows the source current after compensation with unified power quality conditioner.

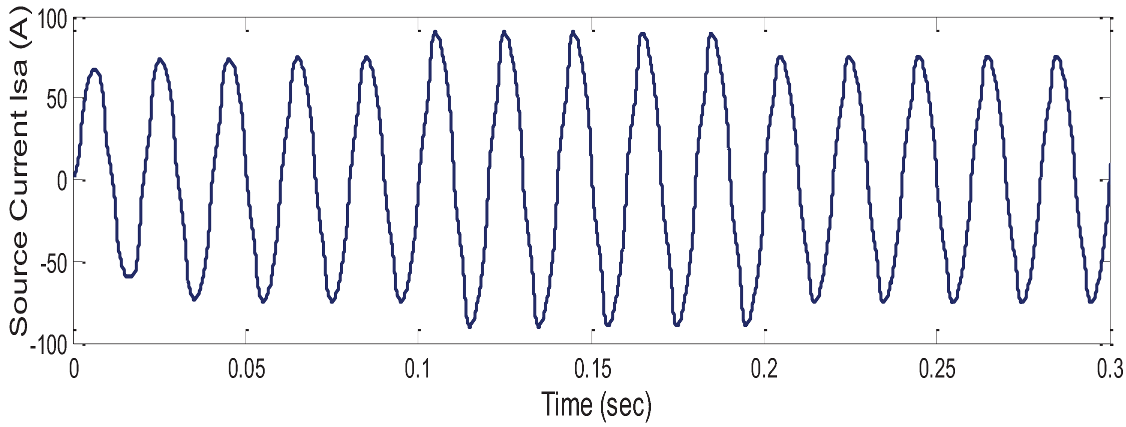


Fig. 5.10 Source current after compensation

From fig. 5.10 it is observed that, the source current after compensation became about sinusoidal.

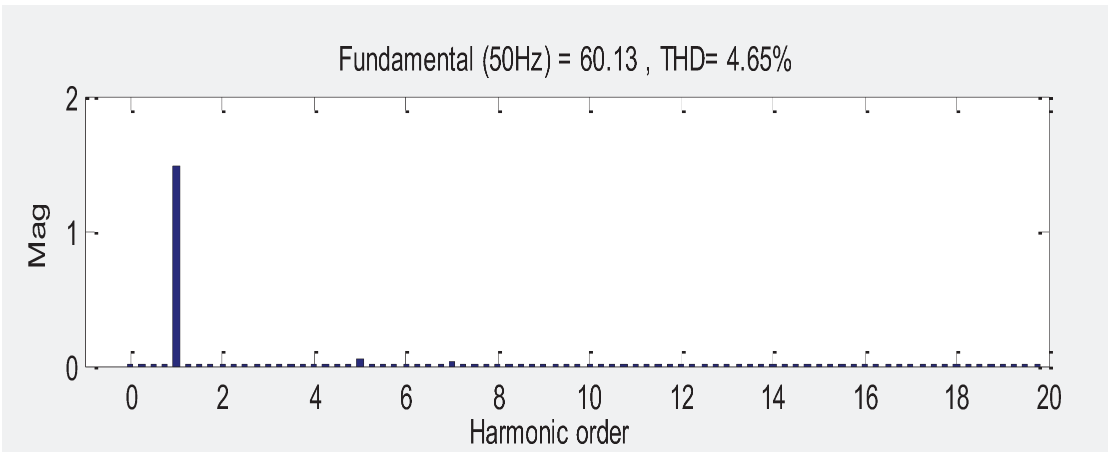


Fig. 5.11 Harmonic spectrum of the source current

Figure 5.11 represents FFT analysis of source current, it shows that the THD of line current is reduced from 23.74 to 4.65 which is below the harmonic limit imposed by the IEEE-519 standards.

As we have discussed in chapter 4 the dc link voltage is one of the important parameter for active power filter. The peak capacitor voltage is the maximum voltage to be supported by the switches, while the lower capacitor voltage will determine the active power filter capability to force its current to follow the intended reference wave form. If the capacitor voltage falls below the peak of PCC voltage, active power filter will not be able to shape its current as intended, and hence mal operation may occur. Figure 5.12 shows voltage across DC link , which is regulated by the PI controller and always tries to track the reference voltage that is 400 volt.

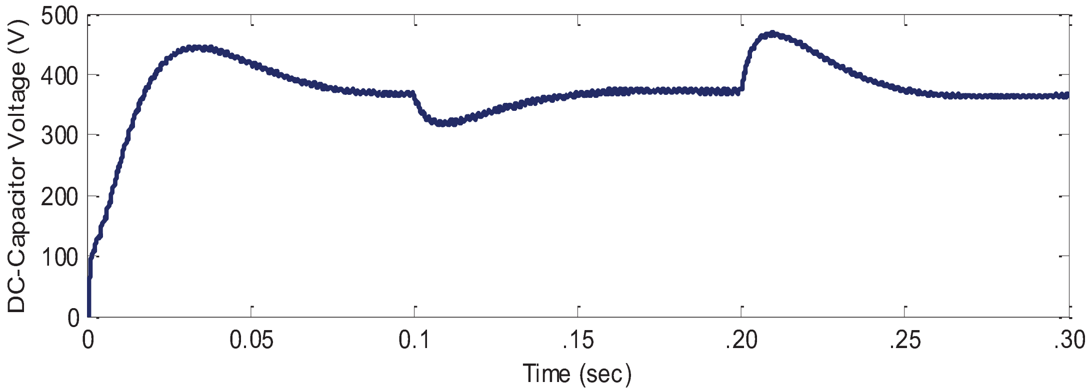


Fig. 5.12 Voltage across Capacitor with PID controller

In chapter 2 we have discussed that presence of nonlinear loads distort the load current as well as line current, which will also distort the voltage across PCC as they pass through the system impedance, in Fig. 5.13, we can observe that blue line is the voltage at PCC which is distorted. While the green line in Fig. 5.13 is the compensating voltage injected by the series part of the UPQC which successfully makes the voltage at PCC sinusoidal as shown in Fig. 5.14.

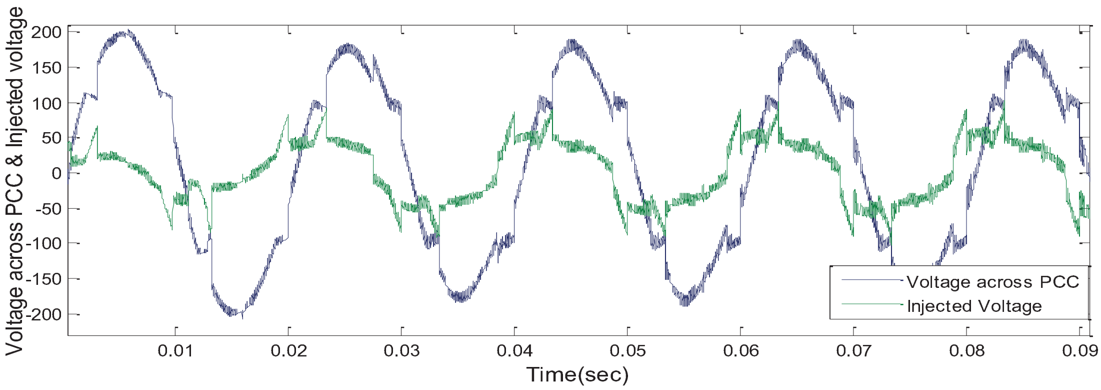


Figure 5.13 Voltage across PCC and injected voltage by series transformer.

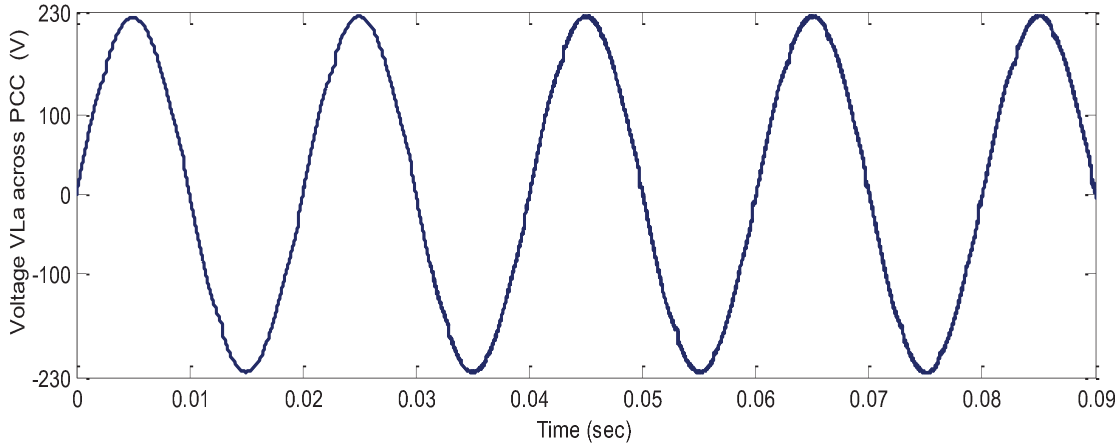
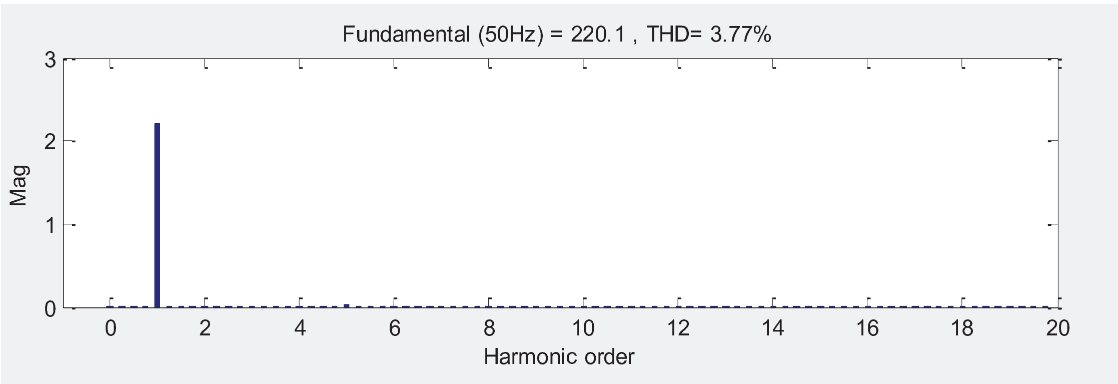


Fig. 5.14 Voltage across PCC after compensation

Figure 5.14 represents voltage across point of common coupling which is about sinusoidal and figure 5.15 represents FFT analysis of voltage across point of common coupling.



5.15 Harmonic spectrum of voltage across PCC

From Fourier spectrum analysis Fig. 5.15 we can observe that the Total Harmonic Distortion in voltage is reduced to 3.77%.

As we have discussed the reactive power compensation is also possible by active power filter. In other words we can say that with the use of active power filter we can compensate not only the current and voltage harmonics but reactive power too, that is after compensation voltage and current both will be in same phase, which makes the power factor is equal to one that is unity power factor. Figure 5.16 represents the same, that is current is in phase with the voltage source.

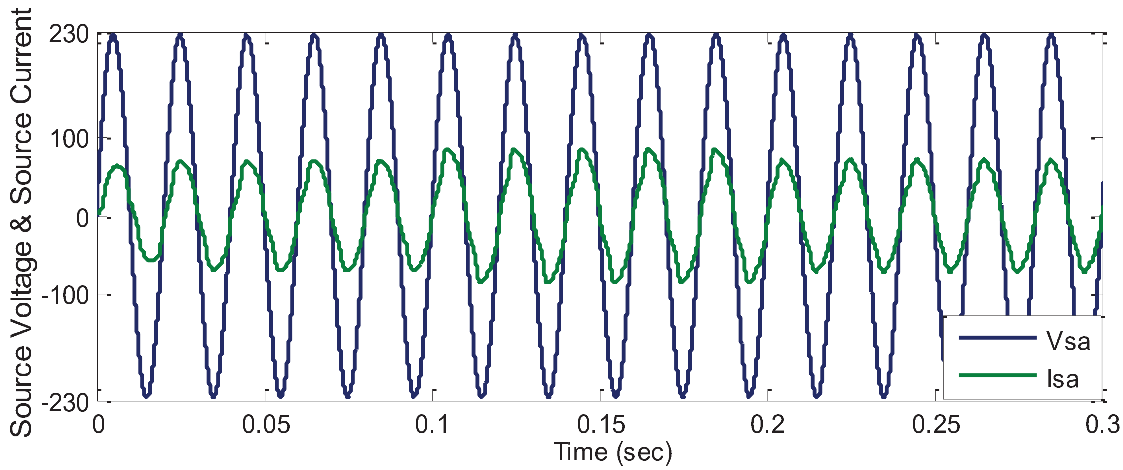


Fig. 5.16 Source voltage and source current are in same phase.

Switching frequency versus time graph is shown in Fig. 5.17 for fixed hysteresis band current control. From Fig. 5.17 we can observe that a wide variation in the switching frequency. But for practical application, it is necessary to keep switching frequency within certain limit.

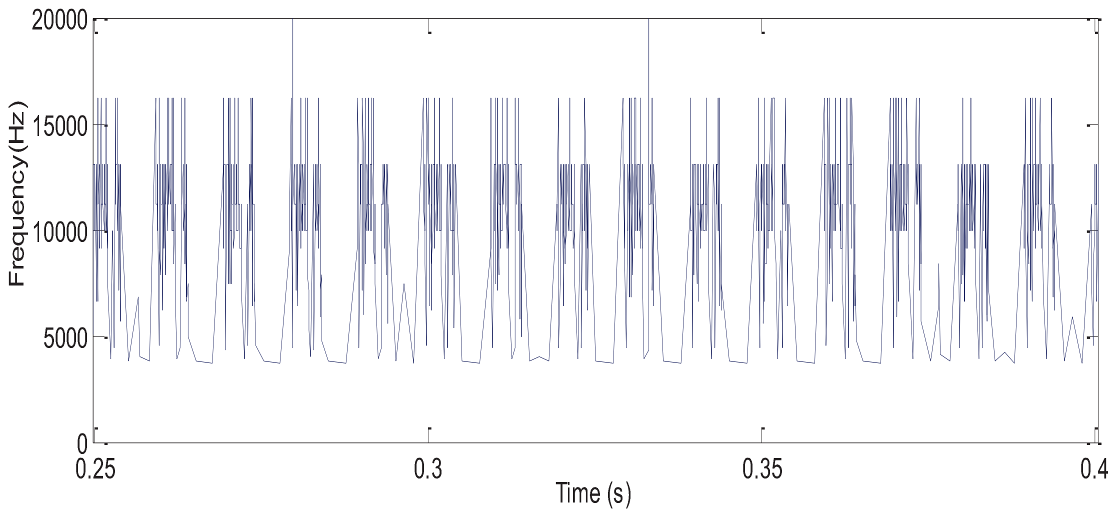


Fig. 5.17 Switching Frequency vs Time for Fixed hysteresis band

To overcome the drawbacks of fixed hysteresis band current control an Adaptive Hysteresis Band Current Controller (AHCC) is used, which maintains the switching frequency nearly constant, by changing the hysteresis band according to system parameters (reference current, source Voltage and dc capacitor voltage).

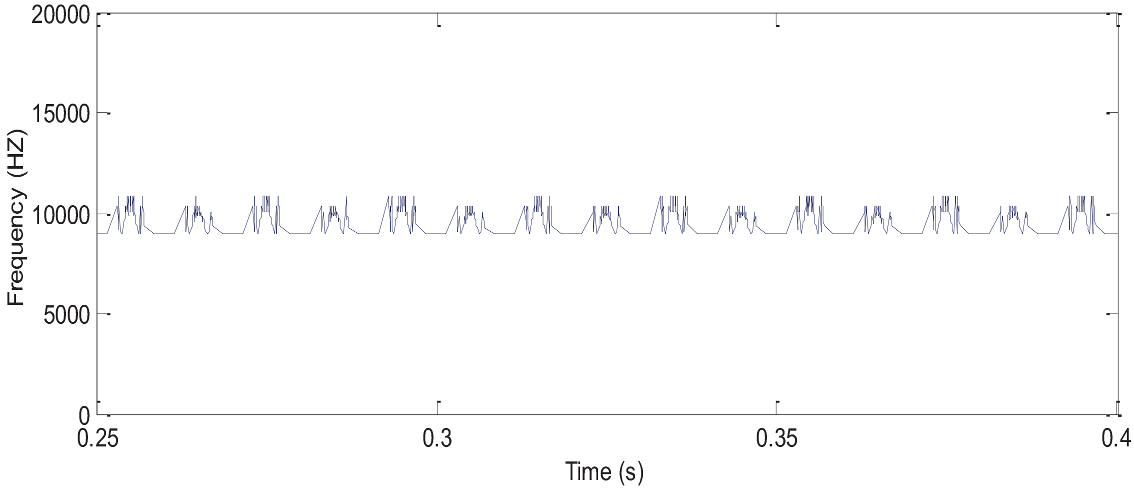


Fig. 5.18 Switching Frequency vs Time for adaptive hysteresis band.

From figure 5.18 we can observe that the switching frequency is about 10 kHz which is the desired switching frequency. We can vary the hysteresis band and hence switching frequency according to requirement of switching devices and their performance by putting the desired frequency value in (19).

CHAPTER 6

CONCLUSION AND SCOPE FOR THE FUTURE WORK

Conclusion

This part of work describes SRF-based controller for the Unified power quality conditioner, which mainly compensate the reactive power along with voltage and current harmonics. The proposed control strategy uses only source current, source voltage, DC link voltage and voltage across PCC, whereas Conventional methods require the measurement of load current, source current, DC link voltage and filter current for shunt APF and source and injection transformer voltage for the series APF so that the numbers of current measurements are reduced and the system performance is improved. To overcome the draw- back of fixed hysteresis band current controller an adaptive hysteresis band current controller has been implemented. The simulation results shows that on nonlinear load, the control algorithm reduces the current as well as voltage harmonics and keeping the utility supply line current sinusoidal.While AHCC successfully maintains the switching frequency almost constant.

Scope for the future work

Real time implementation of the suggested control schemes for UPQC using OPAL-RT to validate the simulation result and experimental investigation can be done on unified quality conditioner by developing a prototype model in the laboratory to verify the simulation results for synchronous reference frame method with both hysteresis band current controller and adaptive hysteresis band current controller.

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